Storm Wave Characteristics

FEMA Coastal Flood Hazard Analysis and Mapping Guidelines Focused Study Report

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Acronyms

2-D	two-dimensional
ACES	Automated Coastal Engineering System
CDIP	Coastal Data Information Program
CEM	Coastal Engineering Manual
CHL	Coastal Hydraulics Laboratory
FEMA	Federal Emergency Management Agency
FIS	Flood Insurance Study
FNMOC	Fleet Numerical Meteorology and Oceanography Center
FNWC	Fleet Numerical Weather Center
GROW	Global Reanalysis of Ocean Waves
IAHR	International Association of Hydraulic Engineering and Research
ICCE	International Conference on Coastal Engineering
JONSWAP	Joint North Sea Wave Project
MII	Meteorology International, Inc.
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NOAA-NCEP	National Oceanic and Atmospheric Administration-National Centers for Environmental Prediction
PWA	Philip Williams and Associates
SEMs	Spectral Energy Models
SOWM	Spectral Ocean Wave Model
SPM	Shore Protection Manual
USACE	U.S. Army Corps of Engineers
WIS	Wave Information Studies

1 INTRODUCTION

This report provides recommendations approaches for improving or preparing the Guidelines and a preliminary time estimate for the four wave-related categories grouped under the Storm Wave Characteristics Focused Study. The four topics and associated need and priority level, which are "C" for Critical and "A" for available, for each geographical area are shown in Table 1.

Table 1. Storm Wave Characteristics Topics and Priorities

Topic Number	Topic	Topic Description	Priority		
			Atlantic / Gulf Coast	Pacific Coast	Non-Open Coast
1	Wave Definitions	Definitions of wave types using contemporary terminology: standardize the terms	A	A	
3	Storm Wave Characteristics	Conversion from Shore Protection Manual to Coastal Engineering Manual	A	A	
4	Swell: Open Coast	Swell exposure: Use hind cast databases, select based on evaluation	A *(C)*	C	
5	Local Seas: Non-Open Coast (Sheltered Waters) and Open Coast	Local seas: Nearshore representation of wind waves rather than offshore hindcast	A *(C)*	C	Atlantic *(A)* Pacific *(C)*
Key: C = critical; A = available; I = important; H = helpful (Recommend priority italicized if focused study recommended a change in priority class)					

It was clear in the scoping phase of this study that Topic 3 included issues on wave generation, but also on wave setup and wave runup. Wave generation related topics developed under Topic 3 were included under Topic 5 in the Local Seas: Non-Open Coast (Sheltered Waters) and Open Coast. Topic 3 was also considered by the Focused Study Leaders for wave setup and wave runup. Topic 3 was considered under other items, and was not pursued independently. The priority level for Topic 5: Local Seas, was assigned after Workshop 1, in consultation with Focus Study Team Members and Leaders. While an available priority was determined for the Atlantic and Gulf Coasts, the priority may be critical in some circumstances. If so, it is expected that this Focused Study report and the upcoming Pacific Coast Guidelines can be used.

In addition to the categories described above, the group also contributed to the definition of the 1-percent-annual-chance event for coastal flood hazard mapping. The term extreme is used in this Focused Study to indicate an event with a low probability of occurrence. No specific value for the probability is associated with this terminology, other than it has a low probability.

The Topics were re-organized after Workshop 1. The revised grouping, which is used in the remainder of this report, is shown below. This grouping is organized to address regional differences and to address similar topics together. These results are summarized in Table 2.

Table 2. Revised Wave Characteristics Topics and Priorities (Post Workshop 1)

Topic Number	Topic	Topic Description	Priority		
			Atlantic / Gulf Coast	Pacific Coast	Non-Open Coast
1	Wave Definitions	Definitions of wave types using contemporary terminology: standardize the terms	A	A	--
3	Storm Wave Characteristics	Conversion from Shore Protection Manual to Coastal Engineering Manual	A	A	--
4 & 5	Sea and Swell	Sea and Swell for the Pacific Coast		C	--
4 & 5	Offshore Wave	Offshore Wave Data for the Atlantic and Gulf Coasts	C		--
5		Nearshore Representation of Southern California Bight		C	--
5	Local Sea (Sheltered Water)	Wave Generation in Sheltered Water	--	--	Pacific C Atlantic A

Key: C = critical A = available I = important H = helpful NE = not essential

The report is organized according to the Guidance document developed by Northwest Hydraulic Consultants on January 29, 2004, and discusses Critical Topics first and available topics next.

1.1 STORM WAVE CHARACTERISTICS FOCUSED STUDY GROUP

The Focused Study Group members were Ian Collins, Dick Seymour, Bob Battalio, Darryl Hatheway, Jeff Gangai, Carmela Chandrasekera, Ron Noble, and Shyamal Chowdhury. Shyamal Chowdhury was the Leader of this Study Group. The group had two phone conference meetings on January 13, 2004, and January 26, 2004, when the group exchanged ideas, discussed directions, shared available information and procedures. The Team Leader was responsible for writing the scope, assembling the team, providing direction and coordination and final drafting of the report. Ron Noble was the internal reviewer and responsible for quality control of this report. Team members shared research and report writing tasks as shown below.

Team Member Responsibilities

Person Responsible	Study Topic
Darryl Hatheway and Ron Noble	Topic 1: Wave Definitions
Jeff Gangai	Topic 3: Conversion from Shore Protection Manual (SPM) to Coastal Engineering Manual (CEM)
Ian Collins	Topics 4 and 5: Swell and Sea for All Coasts
Carmela Chandrasekera and Bob Battalio	Topic 5: Local Sea for All Non-Open Coasts
Dick Seymour	Topic 5: Local Sea for Southern California

2 CRITICAL TOPICS

2.1 TOPICS 4 AND 5: SWELL AND SEA – PACIFIC COAST

2.1.1 Description of Topic and Suggested Improvement

Coastal flooding generally occurs with a combination of high water levels accompanied by large waves. The purpose of this task is to identify and document the sources of wave and swell data that would provide the most useful input for wave transformation models. The wave transformation models would be applied to route the waves to the inshore areas where knowledge of the waves is required to predict wave setup and runup, and overland propagation.

Since the preparation of previous guidelines for the determination of potential coastal flooding, several additional long duration data sources have become available. These have incorporated improved developments in the modeling of winds, wind-wave generation, and swell propagation. Significant improvements in accuracy have been demonstrated by comparisons with offshore buoy recordings and satellite scatterometer data.

The two principal developments have been:

- Improvements in models of wind fields using worldwide meteorological stations and ships. This has led to improved models of the planetary boundary layer to re-analyze historical, measured, barometric pressure data from ships and coastal meteorological stations. The resulting "improved" winds have been compared with the measurements of winds at many offshore buoys.

- Improvements in numerical modeling of wave generation and propagation. Continued research into the physics of energy transfer from wind to waves and subsequent wave propagation have led to significant improvements in the accuracy of wave forecasting and hindcasting.

These developments are now available and have been incorporated into extensive databases of waves and swells.

2.1.2 Description of Procedures in the Existing Guidelines

For the Pacific Coast the existing Guidelines for "Wave Elevation Determination and V Zone Mapping" contain the instruction:

> "No FEMA guidance documents have been published for the Pacific Ocean coastal flood studies. Guidance is to be developed based on existing methodologies recommended by FEMA and coastal states for coastal analyses in the Pacific Ocean. Mapping Partners that are undertaking a flood hazard analysis of a Pacific Coast site should consult with FEMA RPO for that area."

However, the Guidelines do refer to the U.S. Army Corps of Engineers (USACE) Wave Information Studies (WIS) and the availability of offshore and near shore measurements from buoys has been recognized and used by study contractors.

2.1.3 Applications of Existing Guidelines for Pacific Coast

On the Pacific Coast the waves determined from the Fleet Numerical Weather Central, as documented in a report by Meteorology International, Inc. (MII) were used for the Southern California area (by Tetra Tech, Inc.) and the WIS stations for Northern California by OTT Water Engineers, Inc. and for Oregon (Coos Bay County) by CH2M Hill.

The principal source of offshore wave data at the time of the earliest studies was the Fleet Numerical Weather Central (FNWC as summarized by MII, 1977) model for the Pacific Coast. The FNWC wave model, as covered at the time of the development of the guidelines (Tetra Tech, 1982) did not include the effect of hurricane generated swell off the West coast of Mexico and the swell from major storms in the southern hemisphere. The latter wave sources may govern in a few locations due to exposure to the more southerly wave directions.

Currently there are no Guidelines and Specifications for swell data. The FEMA Pacific Coast studies (TetraTech, Ott Water Engineers, CH2M Hill and Michael Baker) have used the WIS data and the MII (FNWC) hindcasts and NOAA data buoys. Other contemporary coastal studies have used the Coastal Data Information Program (CDIP) data buoys (Recordings) and WAVEWATCH III wave hindcasting model (described herein).

2.1.4 Alternatives for Improvement

Overview

Potential sources of wave and swell databases are identified. The general forms of the databases are summarized. These are generally available in a suitable format for input into wave modification models that compute the changes in waves as the shorelines are approached. In turn, such models are essential to predict the wave conditions in the surf zone that would ultimately be used to predict water levels and flooding.

Significant improvements in the analysis of historical meteorology have been developed in recent years. Windfields have been much reanalyzed to yield significant improvement and have been used with so-called third-generation wave hindcast models to yield improvements in wave predictions over long periods (20 years or more). These models have been calibrated and verified by comparison with measured data at offshore buoys. Further improvements are expected.

Definitions

Seas (or Storm Seas) are normally considered to be the result of local storm activity and are being directly influenced by local winds.

Swell is normally considered to be waves that are arriving at a location that is remote from the generation area. Typically, swells have longer periods than waves, but not always so.

Swells and seas may occur together (as is usually the case on the Pacific Coast). When this is so, their energies should be added, corresponding to vector addition (square root of sum of squares) but directions and periods will generally be different.

Data Sources

There have been further developments in wave and swell prediction models since the earlier FNWC data as reported in the MII documents. In 1985 FNWC published the results of a more comprehensive wave climate for many oceans of the world as Spectral Ocean Wave Model (SOWM). This methodology has been improved by several organizations such as:

- CHL Field Research Facility (http://frf.usace.army.mil)
- CHL Operations and Analysis Group (http://sandbar.wes.army.mil)
- National Data Buoy Center (http://seaboard.ndbc.noaa.gov)
- Coastal Data Information Program (http://cdip.ucsd.edu)
- National Oceanographic Data Center (http://www.nodc.noaa.gov)
- Fleet Numerical Meteorology and Oceanography Center (http://www.fnoc.navy.mil/PUBLIC, https://www.fnmoc.navy.mil/PUBLIC/)
- Naval Oceanographic Office (http://www.navo.navy.mil)
- OceanWeather, Inc. (http://www.oceanweather.com)

The listed data sources include measurements from offshore buoys and extensive hindcast data. The measurements are generally somewhat sporadic as the installation and maintenance of offshore wave measuring devices is expensive.

Specific Comments of Listed Sources

CHL Field Research Facility (Coastal Hydraulics Laboratory)

This database of hindcasts is known as WIS (Wave Information Studies). They provide a 20-year hindcast database for 134 selected stations between Cape Flattery, Washington, and Point Conception, California. (WIS Report 17, “Pacific Coast Hindcast Phase III, North Wave Information” by Jensen, Hubertz and Payne, 1989) and 47 selected stations between Point Conception and the Mexican border (WIS Report 20, “Southern California Hindcast Wave Information” by Jensen, Hubertz, Thompson, Reinhard, Borup, Brandon, Payne, Brooks and McAneny, 1992). Figure 1 illustrates the coverage of part of Northern California Coast and Figure 2 shows the Southern California stations. The stations are relatively close to shore.

The WIS data reports for the Pacific Coast are reportedly under major revision. Existing reports (2003) should be used with care as they do not include the contributions from swells from the Southern Hemisphere or from tropical storms. Published WIS results have also been found to be less accurate. Tillotson and Komar (1997) found that “[s]ignificant wave heights derived from the WIS hindcasts are 30 to 60 percent higher than measured by the deep-water buoys and microseismometer.”

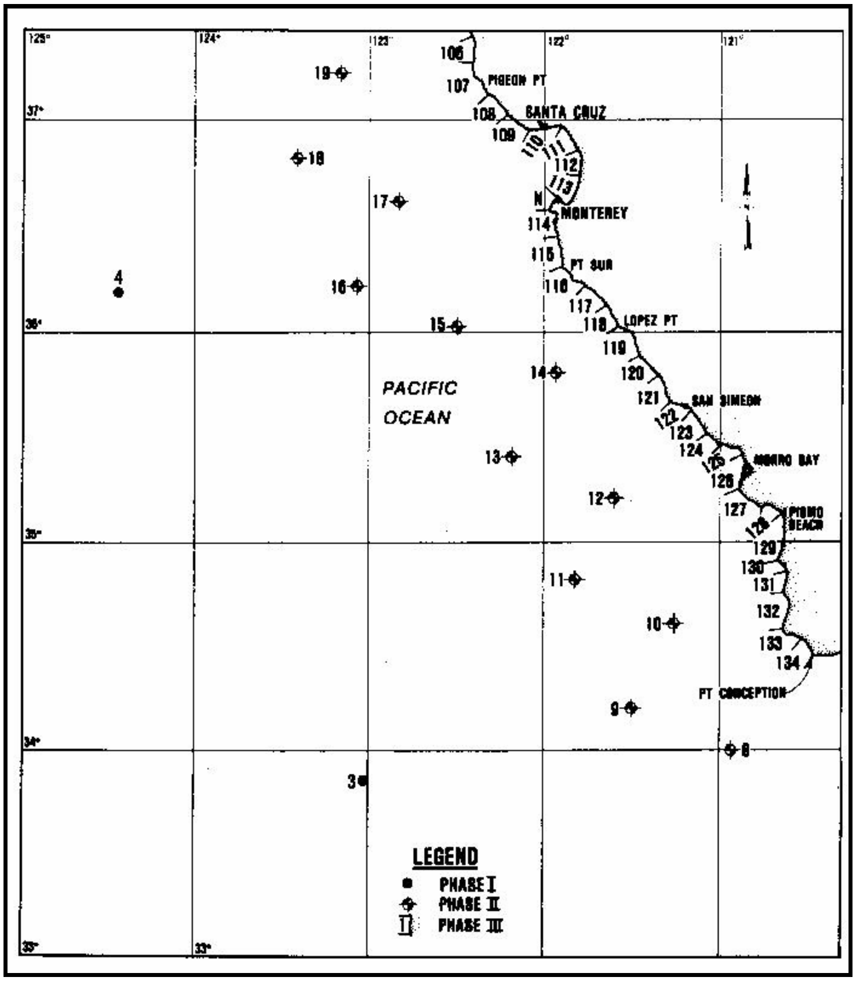

Figure 1. Illustration of WIS hindcast area for northern part of the Pacific Coast.

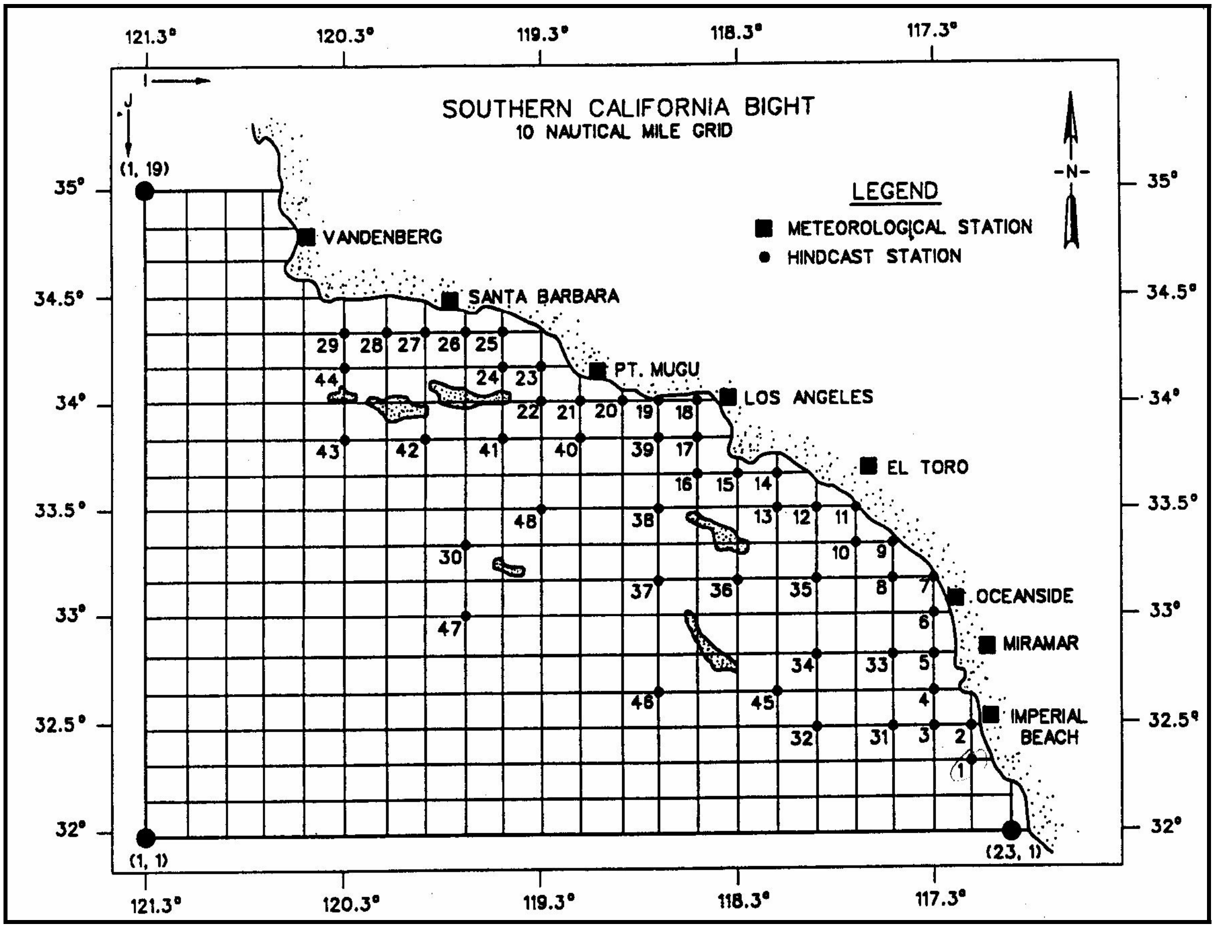

Figure 2. WIS stations in the Southern California Bight.

National Data Buoy Center

The National Data Buoy Center is a branch of NOAA. They have been installing and maintaining offshore meteorological and oceanographic buoys since the late 1960s. Many of these buoys have been in place for a sufficiently long period (typically, 20 years of data, and preferably longer is required to estimate the 0.01 probability extreme event with confidence) that reasonably accurate wave height statistics can be derived. Many other buoy locations are available for limited periods. Such buoys cannot be used for direct statistical prediction of extremes but are still very useful to check wave hindcast models during the overlapping times.

Figure 3 shows an example of the locations of the MetOcean buoys in the Southern California area and Figure 4 shows locations in the North Pacific. Not all of the buoys that are shown on the maps are always present and often the ones shown are removed for maintenance and may be replaced in a slightly different location. Data inventories (dates of installation and recording) are also included on the website. Most wave data are in the form of one-dimensional spectra with summaries of wave height and periods (spectral peak and average). Very few have wave directional information. The wind and wave data from the buoys have been used extensively to check calibration and validity of wave hindcast models.

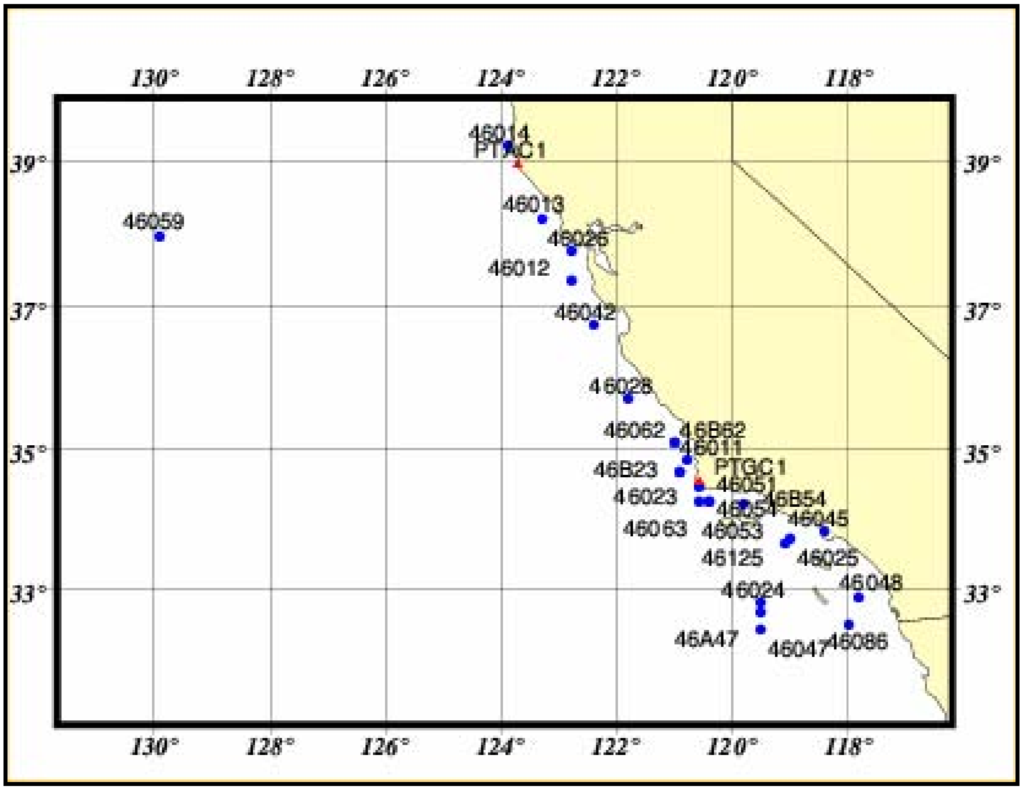

Figure 3. NDBC buoy locations (southern California).

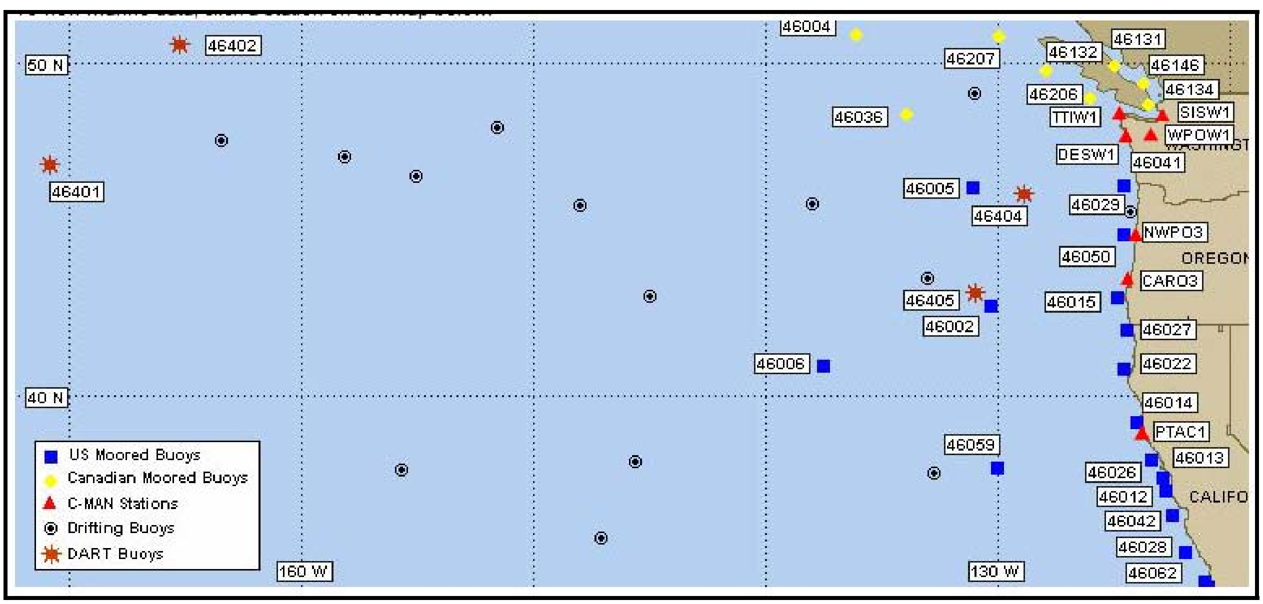

Figure 4. NODC buoy locations in the north Pacific.

Coastal Data Information Program (Mostly in California)

The CDIP consists of a number of nearshore buoys that record directional wave spectra. They are installed and maintained by Scripps Institution of Oceanography under the sponsorship of USACE and the State of California. The program has been expanded recently to include some installations on the Atlantic Coast. Some earlier data included waves measured by pressure sensor arrays.

Figure 5 summarizes the locations of many of the buoys. The buoys are generally located in water depths of 100 to 550 meters. There are a few buoys in shallower water. The duration of available records is generally too short for reliable estimates of conditions that would be characteristic of the 1-percent extreme value but are useful to calibrate and verify wave modification modeling. Previous deployments included bottom-mounted pressure arrays in shallow water. Data from these instruments includes the estimates of wave directions. However, pressure sensors have been discontinued in all but one site at Scripps Institute of Oceanography Pier.

The CDIP program includes a wave forecasting and shallow water swell height modeling capability that provides wave information near the California Coast. These shallow water conditions are covered more extensively in the Wave Transformation Focused Study.

138	BEGG ROCK BUOY	33 22.800	119 39.800	USACE	CDIP	d-01/30/1991
052	SAN CLEMENTE ARRAY	33 24.900	117 37.800	USACE	CDIP	d-05/05/1998
096	DANA POINT BUOY	33 27.506	117 46.003	USACE/CDBW	CDIP	o
092	SAN PEDRO BUOY	33 37.091	118 19.008	USACE/CDBW	CDIP	o
072	HUNTINGTON BEACH ARRAY	33 37.900	117 58.700	USACE	CDIP	d-09/18/2001
027	SUNSET BEACH ARRAY	33 42.300	118 04.200	USACE	CDIP	d-05/24/1990
028	SANTA MONICA BAY BUOY	33 51.230	118 37.920	USACE/CDBW	CDIP	o
104	HERMOSA NEARSHORE BUOY	33 51.791	118 25.280	USACE	CDIP	o
080	SANTA CRUZ CANYON BUOY	33 55.000	119 44.000	USACE	CDIP	d-06/01/1989
103	TOPANGA NEARSHORE BUOY	34 01.383	118 34.698	CDBW	CDIP	n
087	SANTA ROSA ISLAND BUOY	34 02.300	120 05.500	USACE/CDBW	CDIP	d-12/18/1995
089	SANTA CRUZ ISLAND EAST BUOY	34 03.500	119 35.000	USACE	CDIP/CDBW	d-11/30/1995
088	SANTA CRUZ ISLAND WEST BUOY	34 04.200	119 50.000	USACE/CDBW	CDIP	d-12/18/1995
141	PORT HUENEME BUOY	34 05.200	119 10.000	USACE	CDIP	d-04/17/1991
038	POINT MUGU BUOY	34 05.400	119 06.800	USACE	CDIP	d-09/30/1985
005	CHANNEL ISLANDS	34 10.000	119 14.200	USACE	CDIP	d-09/19/1983
081	VENTURA BUOY	34 10.800	119 28.600	USACE/CDBW	CDIP	d-03/08/1995

Figure 5. Summary of CDIP buoy locations and dates of installation.

National Oceanographic Data Center

This agency and website include similar data to the National Data Buoy Center but covers the entire world, not just U.S. waters.

Fleet Numerical Meteorology and Oceanography Center

Fleet Numerical Meteorology and Oceanography Center (FNMOC) prepares weather and wave forecasting for all oceans of the world. An example of the Pacific Ocean data for wave height by direction is given as Figure 6. The basic model is known as WAVEWATCH III. Figure 6 shows a particular presentation of wave height and direction. Additional products include wave period and direction, swell heights by direction, and several other forms. The emphasis of the available data appears to be forecasting. They have a historical database that only goes back to July 1997. This would be too short to use for estimation of extreme waves. However, given that the model is readily available and can be downloaded from the WAVEWATCH site the hindcasting model could be extended by a user as long as the analyzed wind fields for earlier years are prepared or available.

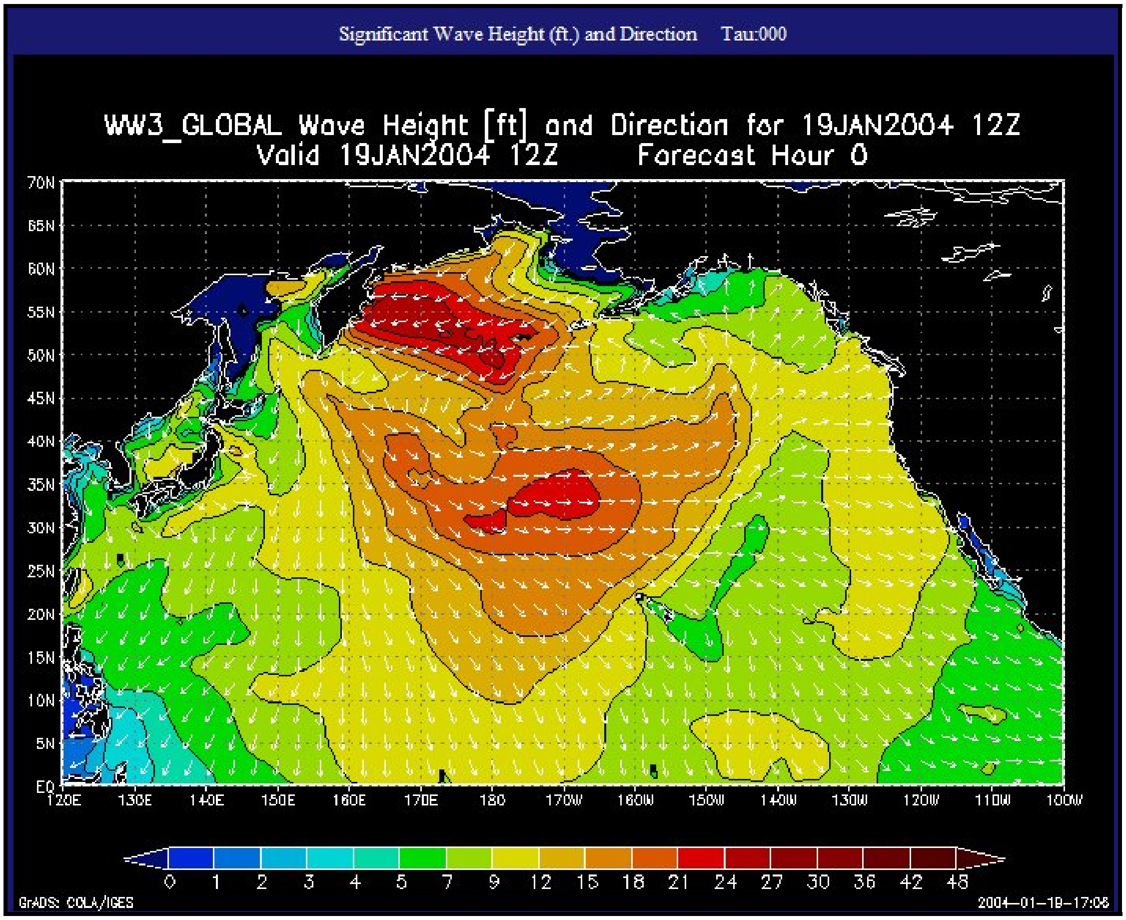

Figure 6. Example of wave forecast from WAVEWATCH III.

WAVEWATCH III (Tolman 1997, 1999a) is a third-generation wave model developed at National Oceanic and Atmospheric Administration-National Centers for Environmental Prediction (NOAA-NCEP) in the spirit of the WAM model (WAMDI Group, 1988; Komen et a1., 1994). It is a further development of the model WAVEWATCH I, as developed at Delft University of Technology (Tolman 1939, 1991) and WAVEWATCH II, developed at NASA, Goddard Space Flight Center (e.g., Tolman 1992). It nevertheless differs from its predecessors on all important points: the governing equations, the models structure, numerical methods, and physical parameterizations.

WAVEWATCH III solves the spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of these equations is that the medium (depth and current) as well as the wave field vary on time and space scales that are much larger than the corresponding scales of a single wave. Furthermore, the physics included in the model do not cover conditions where the waves are severely depth influenced. This implies that the model can generally by applied on spatial scales (grid increments) larger than 1 to 10 km, and outside the surf zone.

The following physical features are extracted from WAVEWATCH III homepage

http://polar.wwb.noaa.gov/waves/wavewatch/wavewatch.html :

- The governing equations include refraction and straining of the wave field due to temporal and spatial variations of the mean water depth and the mean current (tides, surges etc.), and wave growth and decay due to the actions of wind, nonlinear resonant interactions, dissipation (‘whitecapping’) and bottom friction.
- Wave propagation is considered to be linear. Relevant nonlinear effects such as resonant interactions are therefore included in the source terms (physics).
- The model includes two source term options, the first based on cycles 1 through 3 of the WAM model (WAMDI Group, 1988), the second based on Tolman and Chalikov (1996), which is used by FNMOC. The source term parameterizations are selected at the compile level.
- The model includes dynamically updated ice coverage.

Many other products are available, including separate displays of waves, swell and wave periods. The software is available for free download. However, the model requires input in the form of a specified windfield. This would require some effort on the part of a Study Contractor. Although, the WAVEWATCH model would be acceptable, the extra processing of wind data that would be required probably makes it more expensive to apply. For the above reasons the model is not recommended at this time for use in Flood Studies, although it may be acceptable to use if properly applied. The model does not calculate wind-related surge.

Naval Oceanographic Office

This agency generally provides summaries of other oceanographic data, including temperature profiles and currents as well as waves. There are extensive data archives but wave information is generally cross referenced to FNMOC and WAVEWATCH III.

OceanWeather, Inc.

OceanWeather, Inc. is a private company that has specialized in wave hindcasting since its inception in 1977. The particular model that would be most useful for FEMA studies is GROW (Global Re-analysis of Ocean Waves). Figure 7 presents examples showing the locations for which wave data are available. The grids are at 0.625 degrees longitude by 1 degree latitude and cover the entire Pacific and Atlantic Oceans.

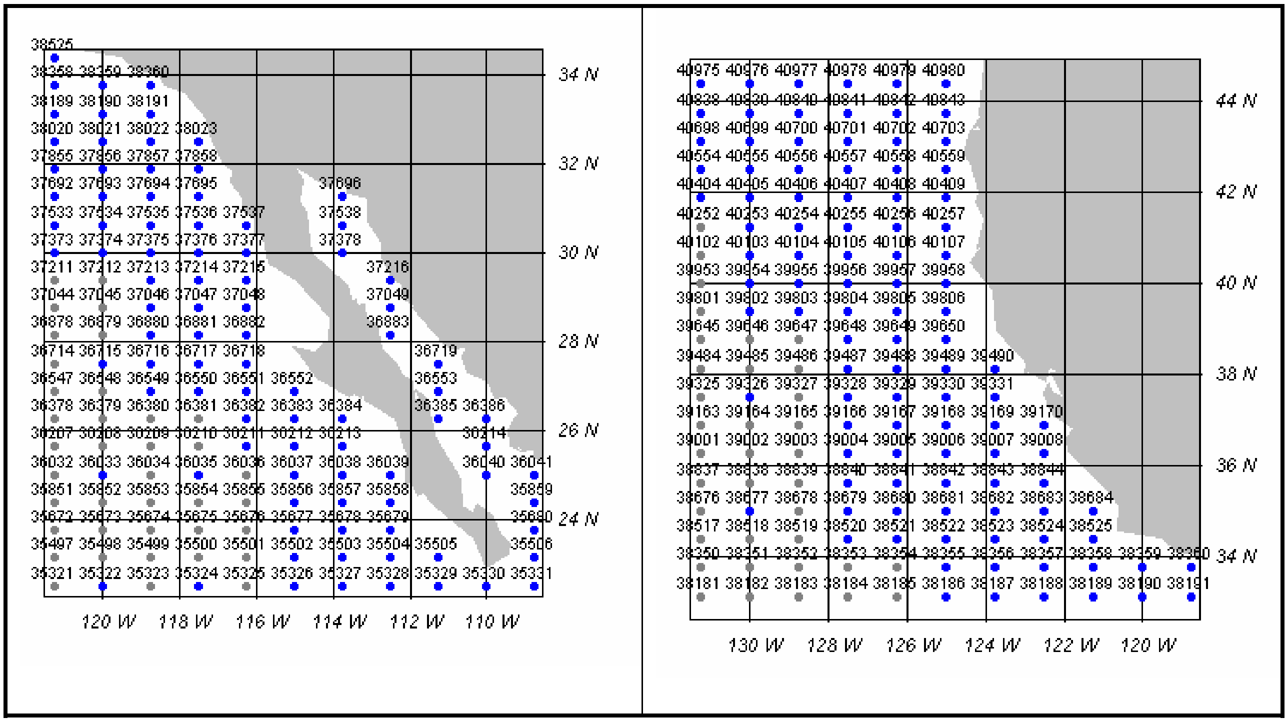

Figure 7. Examples of available locations for GROW hindcasts.

GROW couples Oceanweather's global wave model, planetary boundary layer model, and its vast experience in developing marine surface wind fields to produce a global wave hindcast.

The result is a long-term analysis of the global wave climate that can be applied to offshore structure design, tow-analysis, operability, and other applications where wind and wave data are required. Typical data types include:

- Time series of wind and wave parameters (including sea/swell partitions) in ASCII or OSMOSIS format
- Return period extremes for wind speed, wave height (significant, maximum and crest) and wave period
- Operability statistics expressed as frequency-of-occurrence tables and persistence/duration statistics
- Directional wave spectra

The wave hindcast data are generated following an extensive re-analysis of global windfields. Several technical publications have documented this and compared hindcast wind, waves and swell to measurements by NOAA data buoys and satellite scatterometer data.

The available database includes directional wave spectra every 3 hours over a period of 30 years. The swell directional spectra are on the same time base, but are provided as a separate database. In order to manage this database OceanWeather also sells a software suite known as OSMOSIS. OSMOSIS is an engineering analysis tool for displaying and calculating a variety of metocean hindcast statistics. GROW products are available in OSMOSIS format and are purchased separately from the database.

OSMOSIS permits several Display and Export features:

- DataSelect area of interest by clicking on map or entering location
- Select time period of interest
- Display time series as tables or graphs of all or some variables and dates
- Display tables of normals and extremes computed by Oceanweather
- All tables and graphs can be printed or saved to disc
- Export multiple time series to disc at once by selecting points from a map

Statistical analyses include:

- Frequency of Occurrence tables on any two variables
- Persistence/Duration tables on any variable
- Objective identification of storm peaks based on any variable
- Interactive modification of storm peak selection
- Extremal analysis with Gumbel, Borgman and Weibull distributions
- Scatter plots of time series or storm peaks

2.1.5 Recommendations

Offshore waves become the drivers for nearshore waves that in turn induce wave setup and runup. The “best” sources of offshore waves and swell need to be identified. An assessment of their accuracy and general quality is needed.

For the Pacific Coast, the GROW data is recommended but updated WIS data is under development and is expected to include input from GROW. Consequently this could become the database of choice for the Pacific Coast. The WIS database that is currently available for the Pacific Coast does not include Southern Hemisphere swell or swell from tropical storms. Wave recordings from the CDIP buoys could be used to verify the validity of wave and swell modification modeling between the offshore and the nearshore.

GROW is available as an off-the-shelf product and is presented in the form of directional spectra for both waves and swells for every 3 hours for 30 years or more. This is believed to be the most useful and comprehensive data source. WAVEWATCH III is heavily oriented for use as a forecasting tool but the source code is available and has been used to develop deep water wave statistics for coastal studies (Noble Consultants for USACE, 2003). Two drawbacks to using WAVEWATCH III would be the need to derive, process and set up the required 20–30 years of windfields or limit the database because the data is only archived back to July 1997.

2.1.6 Preliminary Time Estimates for Guideline Improvement

The remaining tasks that can be completed within the time being allocated for the revised Guidelines and Specifications would be:

1. Review the technical publications on GROW and perform a critical analysis to confirm the claimed lack of bias. (40 hours)

2. Examine the detailed reports from GROW and describe the necessary steps to prepare the input data for wave transformations as the waves propagate to shore. (80 hours plus cost to obtain a data set for a selected Pacific Coast station)

3. Recommend a methodology to apply the shallow water wave transformation models to a suitable matrix of GROW directional spectra to ensure complete coverage of the deep water wave properties envelope. (40 hours)

4. Review the available databases for offshore and near shore wave buoys to see whether they can be used as input to shoaling water wave models. (Leave to Study Contractor)

5. Keep in touch with the progress on the revisions to WIS for the Pacific Coast to see whether this database can be used for wave inputs to local wave modification models. (up to 40 hours, as needed)

Table 4 at the end of this document summarizes the estimated hours for these portions of Topics 4 and 5.

2.2 TOPICS 4 AND 5: OFFSHORE WAVE DATA FOR ATLANTIC AND GULF COASTS

2.2.1 Description of Topic and Suggested Improvement

This topic was actually listed as “Available” during the December planning meeting. This is true as long as the methods for wave determination that are given the SPM are considered to be adequate. The procedure takes a “standard” synthetic hurricane and uses the Bretschneider method, which gives wave heights and periods in terms of the hurricane’s central pressure deficit, radius to maximum winds, and forward speed. Such an approximation assumes coincidence of the waves with the peak of the storm surge and assumes that the waves are approaching normal to the shoreline. The method may be adequate since the “controlling” wave height (1.6 times the significant wave height) will often, but not always, be the limit breaking wave at the original shoreline. Wave heights are needed for overland wave propagation, wave runup, and wave setup computations.

However, there may be cases where the Bretschneider hurricane wave approximation is not valid. In such cases, a more complete knowledge of the directional spectrum of waves and swell implies that this becomes a "critical" topic. In such a case, the recommended alternative would be to use the available WIS database or follow the procedures starting with GROW and running an acceptable shallow water wave modification process. The approach would be similar to that described above for the Pacific Coast.

To use a wave height other than the "controlling" wave, an "equivalent" deep water wave height will be needed. This is the *H*o' that is used on many nomographs of wave properties. *H*o' is the equivalent deep water wave height that can be derived from the local wave height after being "de-shoaled" and "de-refracted." In other words, it is what the deepwater wave height would have been if it had not been modified by shoaling and refraction. It allows the use of a local wave (from WIS) or measurement. The effect of energy losses from bottom friction, percolation, and fluid mud bottoms becomes irrelevant. In some cases, if the local wave height has to be derived by wave transformation, the effects of such energy losses have to be included before the derivation of Ho'.

2.2.2 Description of Procedures in the Existing Guidelines

It must be expected that there will be waves present and propagating toward the shore when the 1-percent water level occurs. The present guidelines (Appendix D of the Guidelines and Specifications [*G&S*]) apply primarily to the Atlantic and Gulf Coasts and are summarized in the following.

Three specific approaches are suggested in the existing Guidelines and Specifications:

- Wave data from wave measurements at offshore buoys
- Wave data from hindcasts or numerical modeling based on historical effects
- Wave data from specific calculations based on assumed storm meteorology

It was recommended that two or all three methods be applied where feasible to ensure the most accurate assessment of wave conditions. The *G&S* then include the following:

> "Wave measurements for many sites over various intervals have been reported primarily by the USACE and by the National Data Buoy Center. Available data includes records from nearshore gages in relatively shallow water (Thompson, 1977) and from sites further offshore in moderate water depths (Gilhousen *et al.*, 1990). The potential sources of storm wave data also include other Federal agencies and some State or university programs."

"The USACE is the primary source for long-term wave hindcasts along open coasts. That information is conveniently summarized as extreme wave conditions expected to recur at various intervals for Atlantic hurricanes in "Hurricane Hindcast Methodology and Wave Statistics for Atlantic and Gulf hurricanes from 1956-1975" (Abel et al., 1989) and for extratropical storms in "Hindcast Wave Information for the U.S. Atlantic Coast" (Hubertz, Brooks, Brandon, & Tracy, 1993) and "Southern California Hindcast Wave Information" (Jensen et al., 1992), as examples. In some vicinities, other wave hindcasts may be available from the design activities for major coastal engineering projects."

"Either measurements or hindcast results pertain to some specific (average) water depth. However, the Mapping Partner may need to convert such wave information into an equivalent condition at some other water depth for appropriate treatment of flood effects. The Mapping Partner shall consult the following publications for guidance regarding transformation of storm waves between offshore and nearshore regions, where processes to be considered include wave refraction, shoaling, and dissipation: "The USACE Shore Protection Manual" (USACE, 1984), "Random Seas and Design of Maritime Structures" (Goda, 1985), and "Automated Coastal Engineering System, Version 1.07" (Leenknecht, Szuwalski, & Sherlock, 1992)."

"The Mapping Partner may also consider determining local storm wave conditions by developing a specific estimate for storm meteorology taken to correspond to the 1-percent-annual-chance flood. That can be done with relative ease for deep-water waves associated with a hurricane of specified meteorology, using the estimation technique provided in the USACE Shore Protection Manual (USACE, 1984). For extratropical storms, the ACES program in Automated Coastal Engineering System, Version 1.07 (Leenknecht, Szuwalski, & Sherlock, 1992) executes a modern method of wave estimation for specified water depth, incorporating some basic guidance from the Shore Protection Manual (USACE, 1984) and Random Seas and Design of Maritime Structures (Goda, 1985). The Mapping Partner may prepare an outline of important considerations to assist in developing a site-specific wave estimate."

"The resulting wave field is commonly summarized by the significant wave height and wave period; namely, average height of the highest one-third of waves and the corresponding time for a wave of that height to pass a point. Another useful measure is wave steepness, the ratio of wave height to wavelength: in deep water, the wavelength is 0.16 times the gravitational acceleration, times the wave period squared, that is, ($gT^2/2\pi$). On larger water bodies and in relatively deep water, typical wave steepness is approximately 0.03 for extreme extratropical storms and 0.04 for major hurricanes. The Mapping Partner may use these values for wave steepness to determine the wave period if only the wave height is known and the wave height if only the wave period is known."

2.2.3 Applications of Existing Guidelines for Atlantic and Gulf Coasts (Waves and Swell)

Study contractors on the Atlantic (South) and Gulf Coasts have generally assumed that waves would be present whenever high-water levels occur at the coast because high water is associated with hurricane activity. The general practice has been to use the SPM procedure for "model" hurricanes. Appropriate values of central pressure deficit and size are assumed and deep water significant wave heights and periods computed. Some studies used the local 5 to 10% central pressure depression, and local median values for other parameters such as radius and forward speed (Personal communication, David Divoky). These waves would then be used to determine local setup and runup that would be present at the time of high water.

The existing FEMA guidelines use direct hurricane wind-wave generation models for the major part of the Atlantic Coast and the Gulf of Mexico Coast because the extreme water levels along these coasts are usually controlled by hurricane events where the simultaneous arrival of the highest water levels is accompanied by waves that will be controlled by depth limited breaking. A reasonable approximation of the offshore wave heights is probably adequate. In other words, the waves are limited by breaking criteria. The relatively wide continental shelf also tends to limit the wave conditions along these coasts because higher offshore waves are reduced by non-linear friction effects more than lower waves. Consequently, large differences in offshore wave heights translate into smaller differences near shore. However, the wave setup at the shoreline is sensitive to deep water wave conditions.

For the Northern part of the Atlantic Coast the governing extreme storm may be a Northeaster, although hurricanes from the south should not be neglected.

Currently there are no Guidelines and Specifications for swell data.

2.2.4 Alternatives for Improvement

Overview

Similar databases that have been discussed in the Focused Study report on waves and swell for the Pacific Coast exist for the Atlantic and Gulf Coasts. These include WIS (USACE) for local water depths, WAVEWATCH (U.S. Navy) and GROW (commercial) for deep water.

Definitions

The definitions for sea and swell are the same as presented in section 2.1.5 above. However, for the Atlantic and Gulf Coasts it is expected that at the times of extreme water levels there will be waves related to hurricane condition. Swells have generally been ignored, but swell heights and directions are available in the GROW databases.

Data Sources

Potential data sources for waves and swell can be found at the same locations that were listed in the Pacific Coast section. These include:

- CHL Field Research Facility (http://frf.usace.army.mil)
- CHL Operations and Analysis Group (http://sandbar.wes.army.mil)
- National Data Buoy Center (http://seaboard.ndbc.noaa.gov)
- National Oceanographic Data Center (http://www.nodc.noaa.gov)
- Fleet Numerical Meteorology and Oceanography Center (http://www.fnoc.navy.mil/PUBLIC, https://www.fnmoc.navy.mil/PUBLIC/)
- Naval Oceanographic Office (http://www.navo.navy.mil)
- OceanWeather, Inc. (http://www.oceanweather.com)

The listed data sources include measurements from offshore buoys and extensive hindcast data. The measurements are generally somewhat sporadic as the installation and maintenance of offshore wave measuring devices is expensive.

Specific Comments of Listed Sources

CHL Field Research Facility

WIS provides a 25-year hindcast database for selected points that are relatively close to shore. An example of the station locations is presented in Figure 8.

The WIS data for the Atlantic and Gulf Coasts have recently been updated and are available from the website in several forms. Examples are given in Figures 9 and 10.

National Data Buoy Center

National Data Buoy Center, as described in the previous section, has systems of offshore meteorological and oceanographic buoys in the Atlantic and Gulf Coast regions. Figure 11 shows a part of the coverage on the Atlantic Coast. Not all buoys that are shown on the maps are always present and often the ones shown are removed for maintenance and may be replaced in a slightly different location.

The locations of the buoys in other areas are readily determined at the website. Data inventories (dates of installation and recording) are also given on the website. Most wave data is in the form of one-dimensional spectra with summaries of wave height and periods (spectral peak and average). Very few have wave directional information. The wind and wave data from the buoys have been used extensively to check calibration and validity of wave hindcast models.

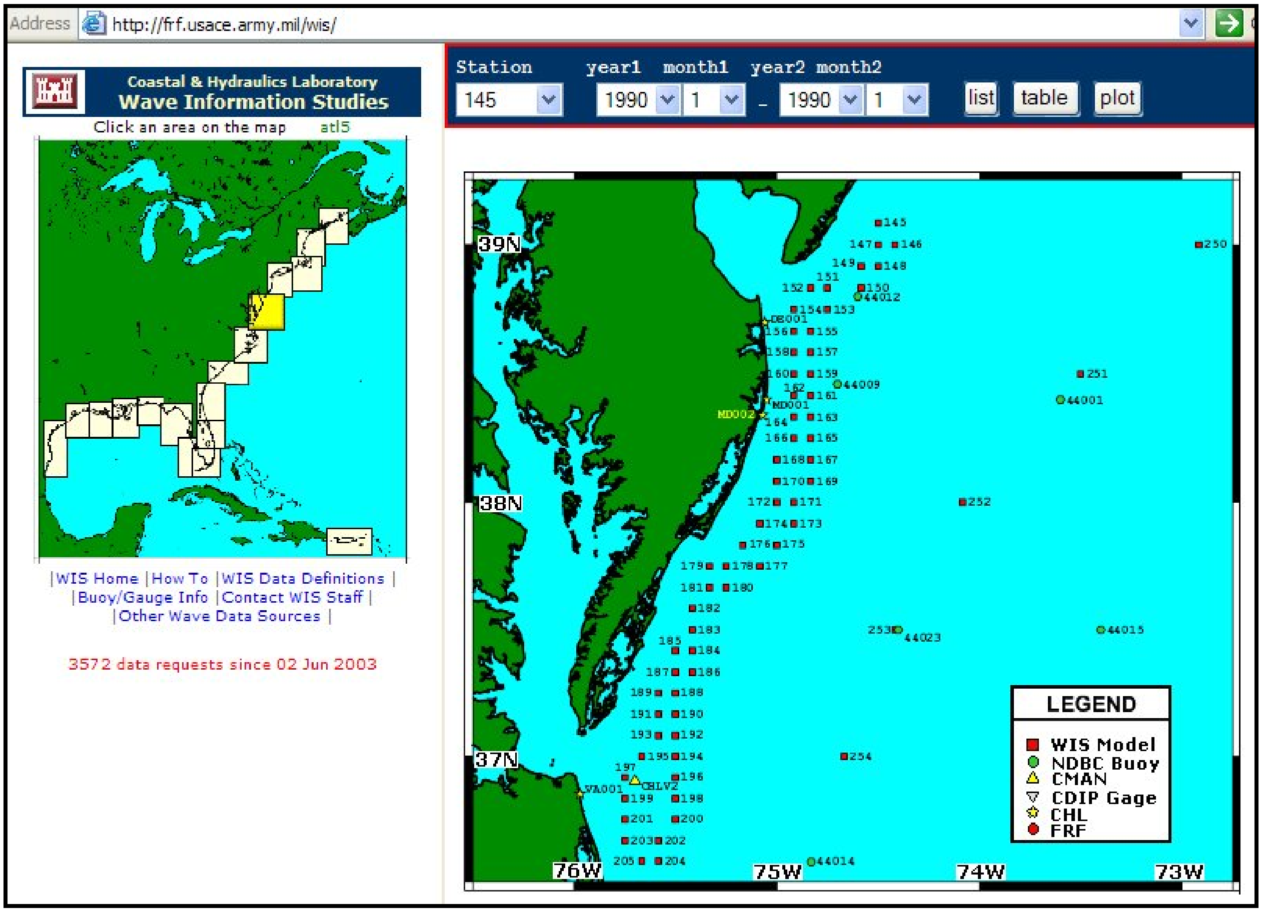

Figure 8. Example of WIS locations.

ip = nuthin

ID	YEAR	MM	DD	HH	LONG	LAT	DPTH	Hmo	DTp	Atp	tmean	wdvmn	wv	wsp	wdir
145	1990	1	1	1	-74.50020	39.08309	17.0	0.34	3.33	3.33	3.33	180.0	180.0	10.5	180.
145	1990	1	1	2	-74.50020	39.08309	17.0	0.55	3.33	3.33	3.42	184.2	184.2	10.3	184.
145	1990	1	1	3	-74.50020	39.08309	17.0	0.79	3.33	3.33	3.52	184.1	184.2	10.2	185.
145	1990	1	1	4	-74.50020	39.08309	17.0	0.93	4.00	3.90	3.86	184.0	182.7	10.0	189.
145	1990	1	1	5	-74.50020	39.08309	17.0	1.08	4.00	4.03	4.10	185.6	186.6	9.9	190.
145	1990	1	1	6	-74.50020	39.08309	17.0	1.14	4.00	4.50	4.40	184.9	179.9	9.6	190.
145	1990	1	1	7	-74.50020	39.08309	17.0	1.30	5.00	4.68	4.68	187.3	181.4	9.6	208.
145	1990	1	1	8	-74.50020	39.08309	17.0	1.50	5.00	4.74	4.88	196.2	192.7	9.5	228.
145	1990	1	1	9	-74.50020	39.08309	17.0	1.59	5.00	5.17	5.03	212.5	223.1	9.4	243.
145	1990	1	1	10	-74.50020	39.08309	17.0	1.65	5.00	5.37	5.10	227.3	190.9	9.5	268.
145	1990	1	1	11	-74.50020	39.08309	17.0	1.42	5.00	5.46	5.00	221.3	181.8	9.6	279.
145	1990	1	1	12	-74.50020	39.08309	17.0	1.26	5.56	5.59	4.96	217.3	179.7	9.8	294.
145	1990	1	1	13	-74.50020	39.08309	17.0	1.22	4.00	5.74	4.95	219.5	181.3	10.0	295.
145	1990	1	1	14	-74.50020	39.08309	17.0	1.20	4.00	6.06	5.01	221.5	163.8	10.4	295.
145	1990	1	1	15	-74.50020	39.08309	17.0	1.21	4.00	6.20	5.07	223.5	165.8	10.7	290.
145	1990	1	1	16	-74.50020	39.08309	17.0	1.25	4.00	3.96	5.04	235.4	278.9	11.0	290.
145	1990	1	1	17	-74.50020	39.08309	17.0	1.29	4.00	3.99	5.03	242.2	281.7	11.4	290.
145	1990	1	1	18	-74.50020	39.08309	17.0	1.34	4.00	4.00	5.07	245.8	283.3	11.7	290.
145	1990	1	1	19	-74.50020	39.08309	17.0	1.37	4.00	4.00	5.24	243.7	286.9	11.7	290.
145	1990	1	1	20	-74.50020	39.08309	17.0	1.41	4.00	3.99	5.44	238.1	287.4	11.7	290.

Figure 9. Example of WIS time series.

1990-1990 ATL WIS STATION: 145 LAT: 39.08 N, LON:-74.50 W, DEPTH: 17 M
PERCENT OCCURRENCES OF WAVE HEIGHT BY MONTH

Hmo(m)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	CASES	PCT
0.00 - 0.49	1.87	1.32	2.34	1.62	2.28	1.91	3.61	2.43	0.79	0.35	1.86	1.03	1876	21.4
0.50 - 0.99	3.88	2.89	3.23	3.71	3.65	5.47	3.44	3.98	3.25	3.52	3.69	2.67	3800	43.4
1.00 - 1.49	1.96	1.91	1.30	2.31	2.25	0.67	1.21	1.74	3.48	2.91	2.00	2.02	2081	23.8
1.50 - 1.99	0.67	1.15	1.05	0.39	0.10	0.17	0.24	0.34	0.69	0.80	0.33	1.48	650	7.4
2.00 - 2.49	0.09	0.33	0.26	0.07	0.18	.	.	.	0.01	0.32	0.23	1.04	222	2.5
2.50 - 2.99	.	0.07	0.19	0.13	0.02	.	.	.	.	0.30	0.11	0.23	92	1.1
3.00 - 3.49	.	.	0.11	.	.	.	.	.	.	0.19	.	0.02	29	0.3
3.50 - 3.99	.	.	.	.	.	.	.	.	.	0.03	.	.	3	0.0
4.00 - 4.49	.	.	.	.	.	.	.	.	.	0.07	.	.	6	0.1
4.50 - 4.99	.	.	.	.	.	.	.	.	.	.	.	.	0	0.0
5.00 - GREATER	.	.	.	.	.	.	.	.	.	.	.	.	0	0.0
TOTAL CASES	743	672	744	720	744	720	744	744	720	744	720	744	8759	

1990-1990 ATL WIS STATION: 145 LAT: 39.08 N, LON:-74.50 W, DEPTH: 17 M
PERCENT OCCURRENCES OF PEAK PERIOD BY MONTH

Tp(sec)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	CASES	PCT
3.0 - 3.9	1.85	1.12	1.00	0.67	1.03	0.69	1.05	0.76	1.31	1.18	2.99	1.04	1287	14.7
4.0 - 4.9	1.64	1.44	1.39	0.91	1.52	0.92	2.25	0.66	0.91	1.70	2.29	1.00	1459	16.7
5.0 - 5.9	0.86	0.86	1.19	0.83	1.18	1.14	2.47	0.42	0.96	0.50	0.11	0.47	962	11.0
6.0 - 6.9	0.90	0.74	0.57	0.48	1.10	1.98	1.42	1.29	0.69	0.51	0.69	1.07	1001	11.4
7.0 - 7.9	0.98	0.63	0.89	0.72	2.16	2.52	0.69	2.64	1.48	1.02	0.33	0.42	1268	14.5
8.0 - 8.9	0.59	0.95	0.53	1.46	0.45	0.39	.	1.08	0.42	1.55	0.13	0.83	734	8.4
9.0 - 9.9	0.86	0.91	1.02	2.02	0.54	0.29	.	0.27	0.05	0.65	0.35	1.22	716	8.2
10.0 - 10.9	0.56	0.63	1.14	0.71	0.37	0.27	.	0.41	0.32	0.37	0.43	1.08	551	6.3
11.0 - 13.9	0.24	0.40	0.66	0.41	0.17	0.02	0.63	0.80	1.94	0.94	0.89	1.22	729	8.3
14.0 - LONGER	.	.	0.10	.	.	.	.	0.15	0.14	0.08	.	0.13	52	0.6
TOTAL CASES	743	672	744	720	744	720	744	744	720	744	720	744	8759	

Figure 10. Example of WIS statistical summaries.

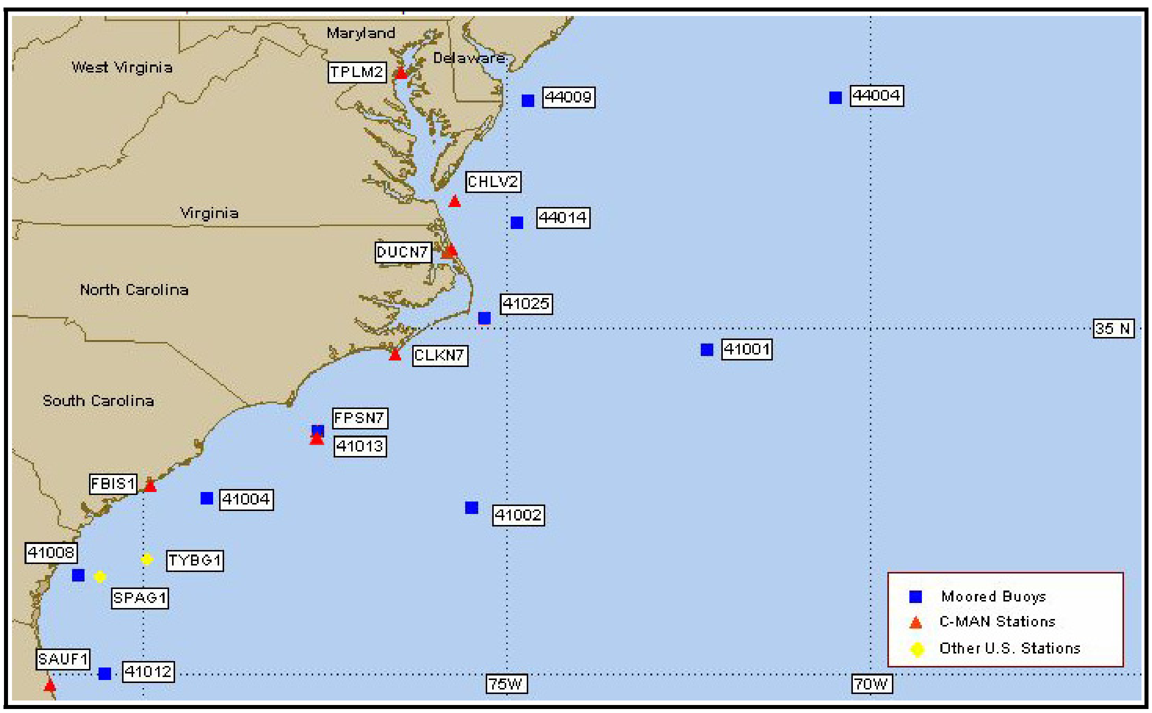

Figure 11. NDBC buoy stations (East Coast, partial).

National Oceanographic Data Center
This agency and website include similar data to the National Data Buoy Center, but covers the entire world, not just U.S. waters.

Fleet Numerical Meteorology and Oceanography Center
FNMOC prepares weather and wave forecasting for all oceans of the world. For the Atlantic Ocean, an example of the data for wave height by direction is given as Figure 12, and Figure 13 presents a sample illustration for swell height versus direction. The basic model is known as WAVEWATCH III. Figures 12 and 13 show a particular presentation of wave height and direction. Additional products include wave period and direction, swell heights by direction and several other forms. The emphasis of the available data appears to be forecasting. The data are available in tabular formats going back to July 1997.

Naval Oceanographic Office
This agency generally provides summaries of other oceanographic data, including temperature profiles and currents as well as waves. There are extensive data archives, but wave information is generally cross referenced to FNMOC and WAVEWATCH III.

OceanWeather, Inc.
Similar to the Pacific Ocean data that were discussed in an earlier section, 30 plus years of hindcast data for deep water that is based on carefully revised wind field analyses has been prepared for the Atlantic Ocean and Gulf of Mexico. Figure 14 presents examples showing the locations for which wave data are available. The grids are at 0.625 degrees longitude by 1 degree latitude.

2.2.5 Recommendations

The presently used procedure as outlined in the existing *G&S* should be retained. Checking the selected storm condition with general wave statistics from WIS should be included. A third check would be to use GROW with a suitable shallow water wave transformation model.

The Technical Working Group and a representative of the USACE (Dr. Don Resio) opined during Workshop 2 that the WIS database had been adequately updated over the years in terms of windfield modeling and is sufficient for wave data needed in the Flood Insurance Studies. Hence, the recommendation was to continue using the WIS database for the Atlantic and Gulf. The Working Group recommended the following items regarding the use of this database:

- Investigate the appropriateness of using either the 100-year significant wave height or the 20-year maximum wave height while modeling WHAFIS;
- Clarify use of equivalent deep water condition**;** and
- Clarify extrapolation to 1-percent-per-year risk level.

2.2.6 Preliminary Time Estimate and Cost for Guideline Improvement

The estimated time required for development of guidelines based on the use of WIS database is approximately 60 hours.

Table 4 at the end of this document summarizes the estimated hours for these portions of Topics 4 and 5.

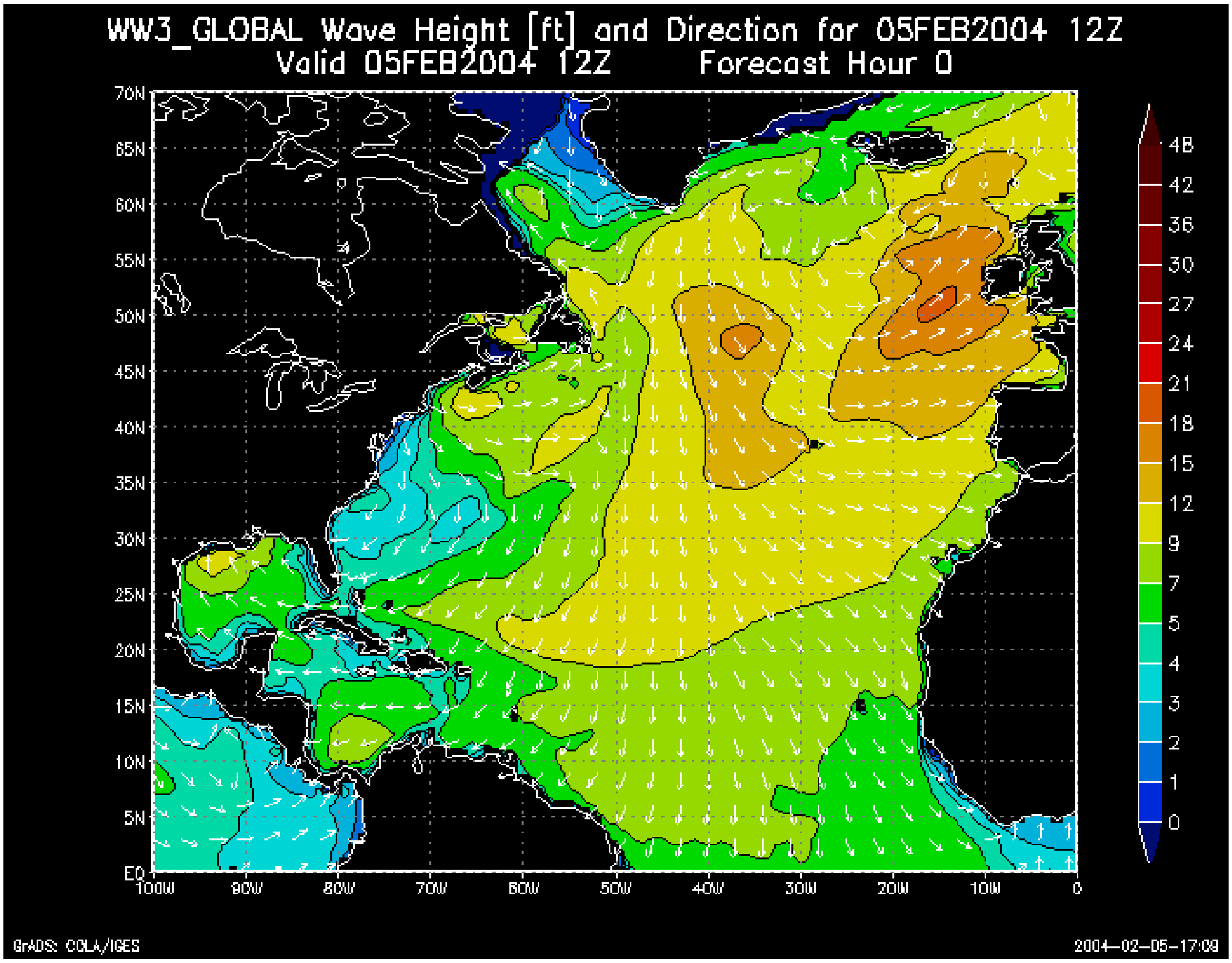

Figure 12. Example of wave forecast from WAVEWATCH III.

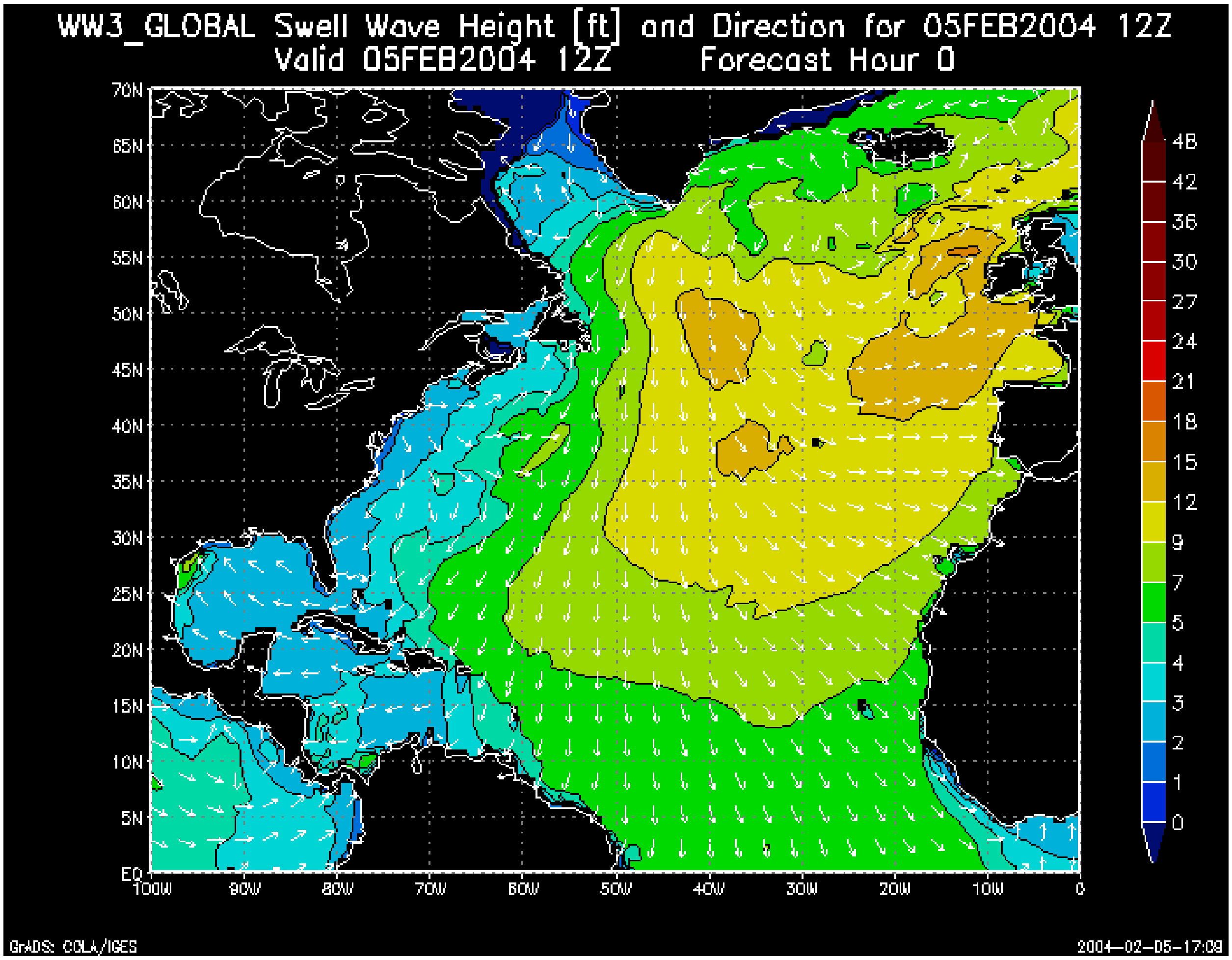

Figure 13. Example of swell forecast from WAVEWATCH III.

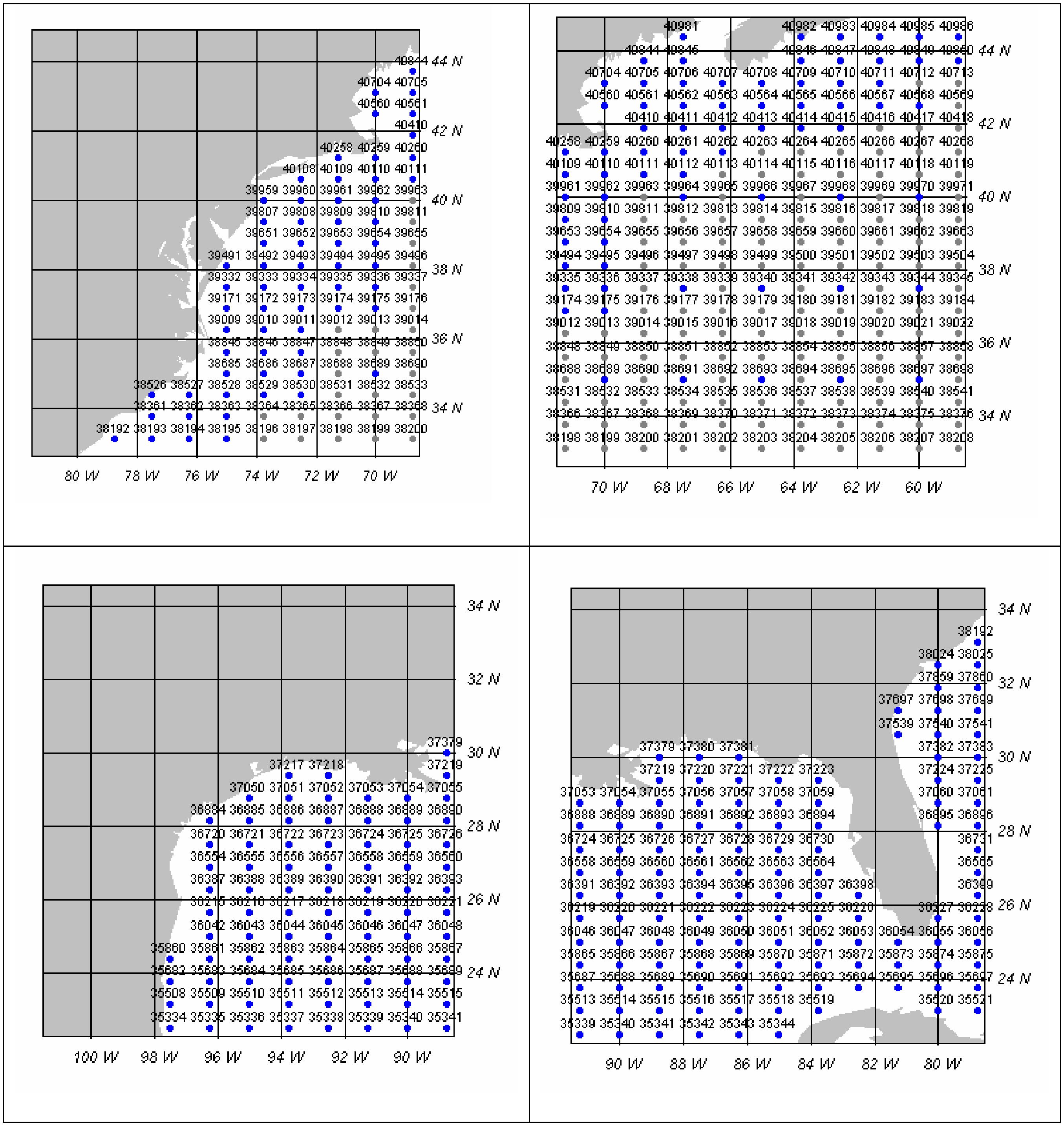

Figure 14. Examples of available locations for GROW hindcasts.

2.3 TOPIC 5: USE NEARSHORE REPRESENTATION OF WIND WAVES RATHER THAN OFFSHORE WAVE HINDCAST- SPECIFIC TO SOUTHERN CALIFORNIA BIGHT

2.3.1 Description of the Topic and Suggested Improvement

In the Southern California Bight (Point Conception to the Mexico border) the shelf is extremely broad and complicated by many islands and shoals. Deep water directional spectra are typically measured or hindcast at the edge of the shelf and wave transformation models that ignore wave generation or dissipation are used to predict nearshore wave conditions. The higher frequency portion of the spectrum (typically periods less than 9 seconds) can be affected by wind conditions encountered during the transit across the shelf. This process is difficult to model because of the lack of wind data and a very complicated wind field. An approach is needed to resolve the impact of local winds on high frequency portion of the spectrum for the Southern California Bight.

2.3.2 Description of the Procedure in the Existing Guidelines

There are no existing Guidelines on this topic. However, CDIP assumes that there is no wind-induced change in the spectrum in the Southern California Bight.

2.3.3 Applications of Existing Guidelines to Topic

This issue was not resolved in past Flood Insurance Studies.

2.3.4 Alternatives to Improvement

There are three alternatives for resolution of this issue. Alternatives are: (a) assume no wind-induced change in the spectrum, (b) attempt to model wind-induced changes, or (c) treat changes to the wind wave portion of the spectrum as an independent variable and use joint probability analysis techniques. Alternative (a) is presently used in the CDIP model. Alternative (b) requires the development and validation of a wind model of much higher spatial resolution than is presently available and could not be accomplished at present. Because the generation area for extreme swell events is typically very distant from the Bight, the local winds cannot be inferred from measured or hindcast wave data at the shelf edge. Alternative (c) considers that winds over the shelf are independent of the height of the extreme waves.

2.3.5 Recommendations

Substantial nearshore data exist to validate the magnitude of changes to the high frequency part of the spectrum during large events. A study of these data should be undertaken and the errors evaluated to determine if they are significant. This may require a subregional approach (i.e., wind effects in the Santa Barbara Channel may differ significantly from those off San Diego County). If the potential error is small, then alternative (a) in 2.3.4 should be used to establish the standard database of nearshore waves in Southern California. Note that this would result in a uniform approach being taken for the entire West Coast wave database because the broad shelf problem does not exist elsewhere on this coast. If the error is too large to be ignored, then a separate database of measured variations in the wind wave spectra should be undertaken. This will allow for the correction to be treated as an independent variable additive to the modeled nearshore spectrum.

2.3.6 Preliminary Time Estimate

The task could require from 120 to 140 hours, depending on whether alternative (a) or (c) in 2.3.4 is taken. Table 2 at the end of this document summarizes the estimated hours for this portion of Topic 5.

2.4 TOPIC 5: WAVE GENERATION IN SHELTERED WATERS – PACIFIC COAST

2.4.1 Description of the Topic and Suggested Improvement

Local wind conditions typically control wave heights in sheltered waters (non-open coast), such as Chesapeake Bay, San Francisco Bay, and Puget Sound. Storm seas in sheltered waters are typically limited by the size and shape of the water body, called “fetch-limited” seas. The procedures for estimating seas in this situation are referenced in the *G&S* for the Gulf and Atlantic Coasts, and the Great Lakes. The references refer to the USACE Shore Protection Manual (1984) and the USACE Automated Coastal Engineering System (1996) (ACES). No *G&S* are available for the Pacific Coast. The suggested improvements entail:

- Enhancing the *G&S* to include better guidance for calculating seas in sheltered waters;
- Updating the *G&S* to be consistent with the recent USACE Coastal Engineering Manual;
- Including improved methodologies used in the recent Region X flood studies; and
- Including contemporary methodologies, specifically third-generation wave generation models now widely available and in use.

2.4.2 Description of Procedures in the Existing Guidelines

There are no *G&S* procedures for the Pacific Coast. In this case, guidance can be derived from the *G&S* for other geographical areas. The same guidance is provided in the *G&S* for the other regions: Section D.2.2.7 Storm Wave Characteristics (page D-24 through D-26) for the Gulf and Atlantic Coasts, and Section D.3.2.6 Offshore Wave Characteristics (pages D-117 through D-121) for the Great Lakes. The guidance refers to the USACE SPM (1984) and ACES (1996) procedures for wind wave generation. The more involved analysis procedure is recommended where wind wave generation fetches are restricted by the complex geometry of water bodies such as sheltered waters. The method entails calculating a “restricted fetch” as the weighted average of a fan of fetches arrayed around the primary wind direction selected. This is described in the following section, Procedures for Restricted Fetches. This is one of several restricted fetch methods. This methodology is well documented in the USACE SPM and ACES listed above, including very specific guidance on the selection of wind parameters, adjustments to wind parameters for site conditions, and application of wind wave generation equations for both deep and shallow water (relative to generated wave length).

2.4.3 Application of Existing Guidelines to Topic-History and/or Implications for the NFIP

The existing *G&S* listed above are serviceable, but are based on older technology. A recent study in Region X (Sandy Point, Whatcom County, Washington – located in the Strait of Georgia) adopted an enhanced version of the restricted fetch method, called the "composite fetch" method (PWA, 2002). The USACE have updated their coastal analysis guidance with the Coastal Engineering Manual (USACE CEM, 2003), which supercedes the Shore Protection Manual (USACE SPM, 1984). Specifically, the wind wave generation equations for shallow water have been updated. Also, as noted in the CEM, more advanced and convenient computer-assisted analysis methods by the USACE and others are readily available and being used by many persons. These models are not presently approved for use on FEMA FISs.

2.4.4 Alternatives for Improvement

Overview of Wave Generation in Sheltered Water

Waves in sheltered water are characterized by locally generated waves (wind-waves) rather than swells (waves that have traveled some distance away from where they were generated).

Currently approved FEMA methods for wave generation are the SPM and ACES for restricted fetch wind growth and MIKE OSW model for deep and intermediate depth applications.

A discussion on wave hind-casting procedures is available in the CEM, (2003). There are two general types of prediction methods:

- **Empirical prediction methods:** These are based on the principle that universal laws govern interrelationships among dimensionless wave parameters. Relations between wave generating parameters and wave conditions have been established using wave observations during the 1940s and 1950s, and updated with more recent studies. The SPM and ACES methods traditionally used in FEMA studies are Empirical Prediction Methods.

- **Spectral Energy Models:** These are based on an energy balance equation that accounts for wave propagation processes and processes that add or remove energy from a particular frequency and direction component, at a fixed point at a given time. Spectral Energy Models have developed into first-generation, second-generation and third-generation models with successive improvements in wave prediction. The third-generation models are widely used today in deep-ocean, shelf-sea wave models such as WAM (WAMDI Group, 1988). In the present context other models that can be applied to shallower water are considered, such as SWAN, STWAVE and MIKE21 OSW).

Improved methods ranging from enhancements to the SPM (empirical prediction) methods to more advanced computer-aided analysis approaches are available. The more advanced computer-based Spectral Energy Models or wave action model are considered superior, but application procedures need to be developed for coastal flood studies.

The alternatives for improvement include:

- Updating the *G&S* to be consistent with the recent USACE Coastal Engineering Manual;
- Enhancing the *G&S* to include better guidance for calculating seas in sheltered waters;
  - Including improved methodologies used in the recent Region X flood studies; and
  - Including contemporary methodologies, specifically third-generation wave generation models now widely available and in use.

Technical Background

Existing Procedures – Empirical Prediction Models: Procedures for estimating storm seas in sheltered waters have traditionally followed the USACE Shore Protection Manual (SPM, 1984), classified as Empirical Prediction Models herein.

SPM Procedures

The SPM procedures are defined in Volume 1, Chapter 3, Section IV, Estimation of Surface Winds for Wave Prediction; Section V, Simplified Methods for Estimating Wave Conditions; and Section VI, Wave Forecasting for Shallow Water. The procedures are detailed in "cookbook" fashion, with enough technical background to allow appropriate enhancements. The heart of the procedures is the Sverdrup-Munk-Bretschneider (SMB) set of equations that relate wind speed, duration, and fetch to wind wave height and period. Modified equations are provided for shallow water (relative to wave length).

A key component of the SPM method is an iterative procedure to identify the fetch limited (maximum) seas. A wind speed is typically selected based on extremal analysis. Wind fields are assumed to include a distribution of speeds and durations, and each wind speed averaged over a particular duration (SPM, page 3-26). The wind field can therefore be considered as an array of wind speed – duration pairs, with faster speeds associated with shorter durations. This is depicted graphically in Figures 15 and 16 (SPM, Figures 3-12 and 3-13 of Pages 3-28 and 29). To calculate fetch limited seas, the fastest wind speed with long enough duration must be selected. Typically, this is accomplished by starting with a high wind speed, calculating the fetch-limited wave height, and checking that the duration-limited wave height is not smaller. If it is, then a slower wind with longer duration is tried. This iteration is repeated until the maximum fetch limited condition is established.

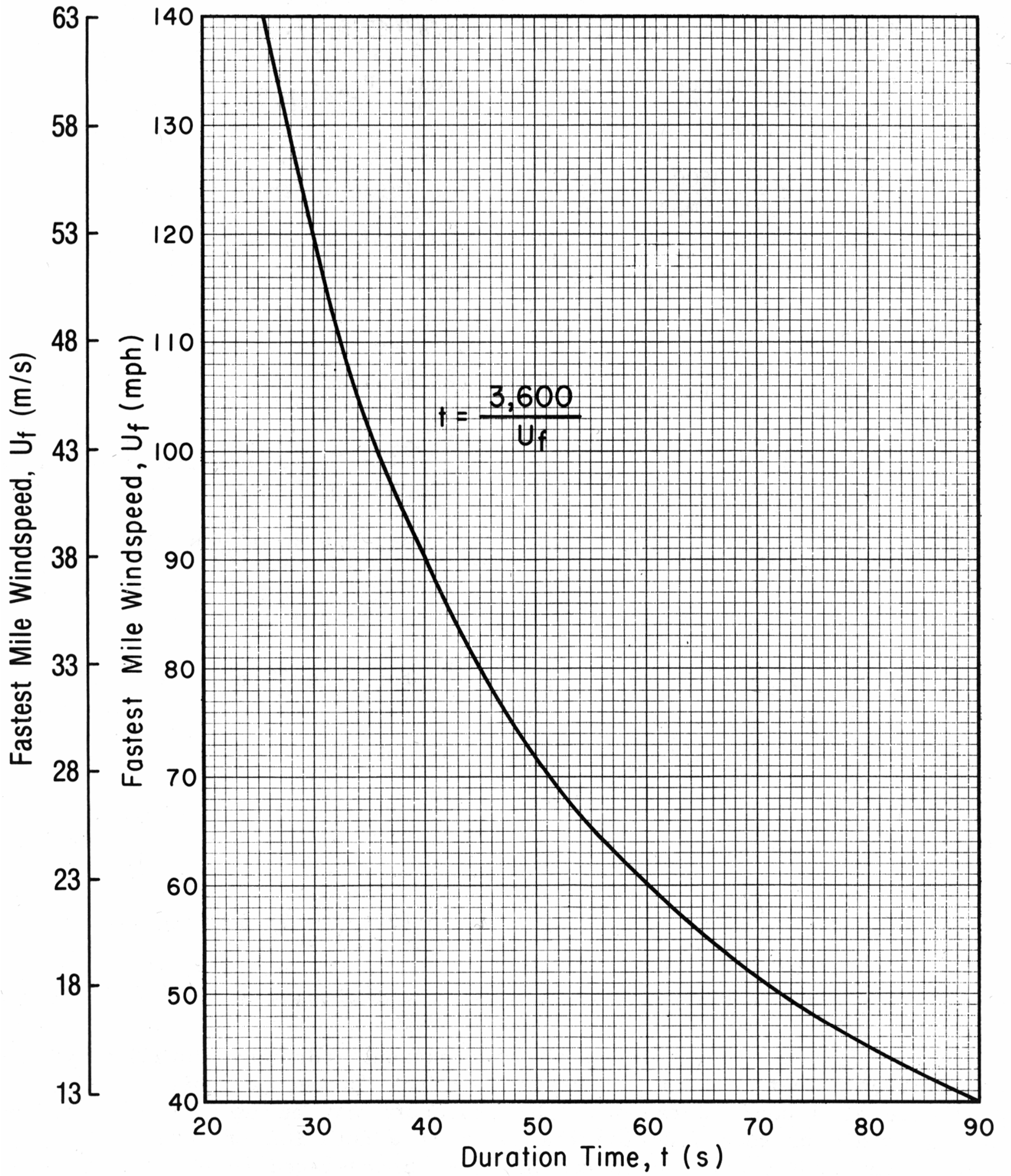

Figure 3-12. Duration of the fastest mile windspeed as a function of windspeed.

Figure 15. Fastest mile windspeed vs. duration.

(Source: Shore Protection Manual, 1984)

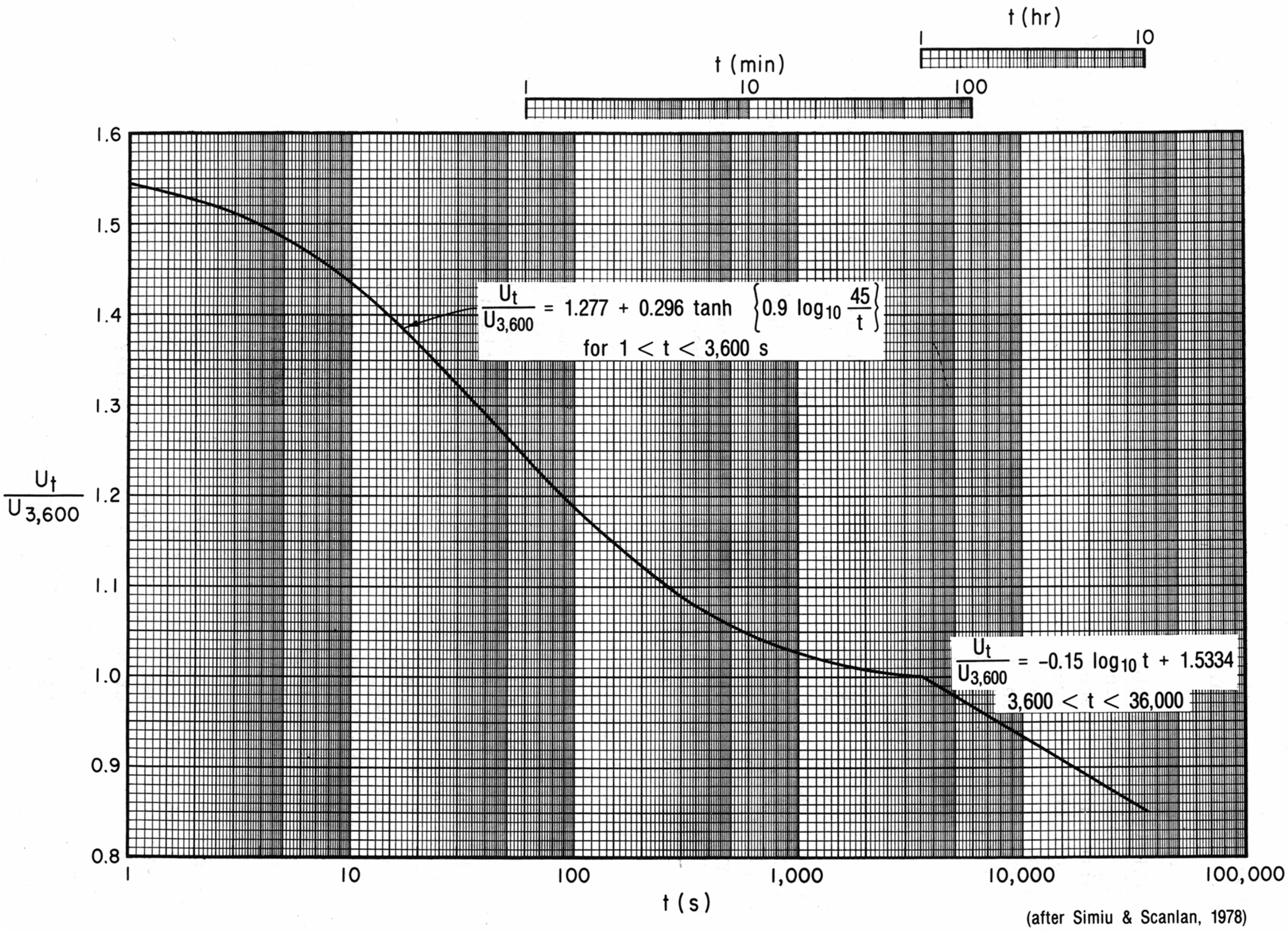

Figure 3-13. Ratio of windspeed of any duration, U_t, to the 1-hour windspeed, U_{3600}.

Figure 16. Windspeed ratio to 1-hour windspeed vs. duration.

(Source: Shore Protection Manual, 1984)

Procedures for Restricted Fetches

Special procedures are often applied for water bodies (embayments) with irregular planforms not easily represented by a single fetch length. This is typically called a “restricted fetch” condition. There are several ways of addressing a restricted fetch condition. The SPM notes that one procedure for addressing restricted fetch conditions, called the “narrow fetch” or “effective fetch” method, is no longer considered appropriate. This older method shortened the fetch based on considering the fetch width. This was based on the observation that wind waves were smaller in restricted fetch areas than open water areas. However, detailed field data indicated that the directional spread of wind waves was most narrow at the spectral peak, and therefore a simple shortening of the fetch could underpredict height and period. In an irregular embayment with the main axis of the open water in line with the primary wind direction, a straight-line fetch provided better results than the “effective fetch” method (SPM, page 3-51). However, the USACE does allow for restricted fetch analysis in cases where a straight line fetch may underpredict wave height and or period, such as when there are multiple but divergent open fetch areas, or the primary wind direction is not aligned with the axis of a longer open water area. These methods are called “restricted fetch” methods (Figure 17 from *G&S*, Figure D-37, page D-121).

ACES Method

The ACES method extends the standard SPM methods to account for restricted fetches. This method is referenced in the *G&S*, and was developed by the USACE. It is called the **ACES Method**, based on the name of the suite of computer programs within which the method is provided (Automated Coastal Engineering System [ACES] Version 1.07, USACE, 1992).

One wind direction and several radial fetch directions (up to +/-90 degrees) are considered. First, the minimum wind duration for a wave field to become fetch limited is evaluated. Then, the character of wave growth is determined (duration limited or fetch limited) and depending on the character, appropriate equations are used to estimate the wave conditions. Winds are not restricted to one direction during storm events and the winds from more than one direction can affect the wave growth.

The wave direction is found by maximizing an expression (product of a weighted fetch length and the weighted cosine of the angle between the fetch and the wind direction), which is assumed to then yield the maximum the wave period. The spectrum-based wave height (Hmo) corresponding to the above condition is calculated. The method does not explicitly consider energy transfers from the adjacent fetches in this approach. However, the method is based on the consideration of these processes. To provide a foundation for consideration of other restricted fetch methods, the physical processes are outlined below.

Guidelines and Specifications for Flood Hazard Mapping Partners

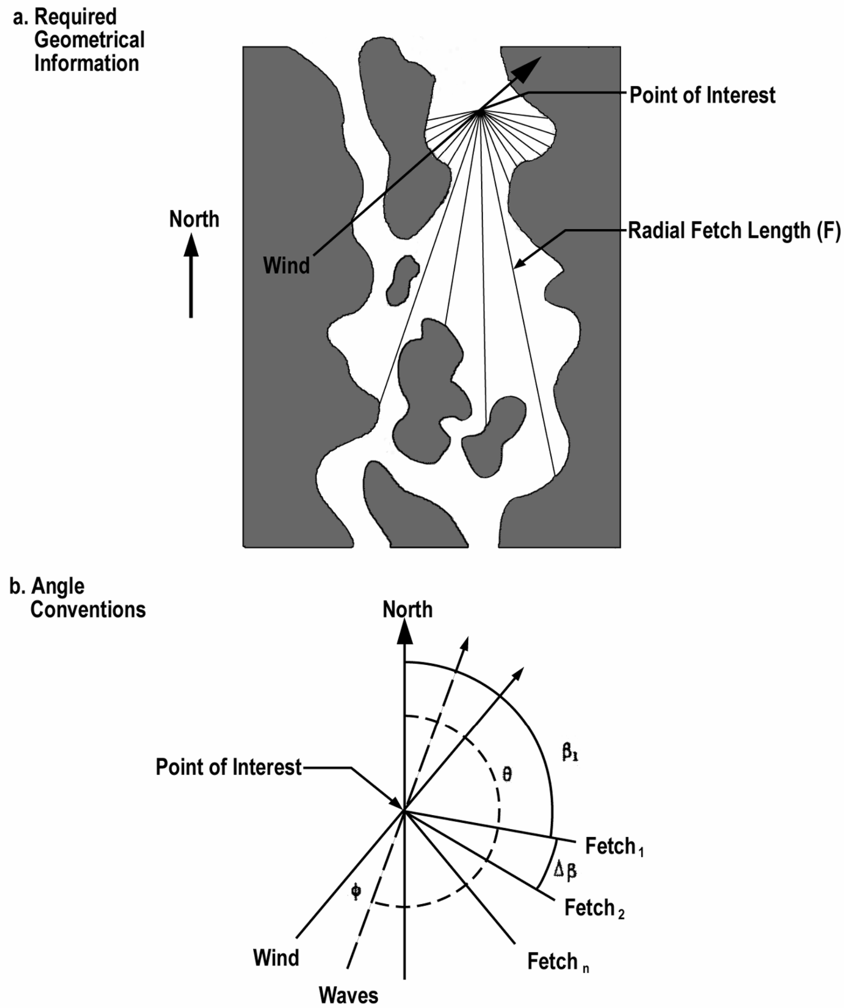

Figure D-37. Outline of Geometry for Wave Development on Restricted Fetches, from ACES Direction of Wave Development (θ) is Defined by Maximizing the Product $[(F_{\phi})^{0.25} \cdot (\cos \phi)^{0.44}]$.

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Figure 17. Illustration of restricted fetch method.

(Source: Appendix D, Guidelines and Specifications for Flood Hazard Mapping Partners, FEMA, 2002)

Directional Wave Spectra in the Wave Generation Area

Within the wind wave generation area, seas have a broad directional distribution (Goda, 1985, Section 2.3.2; Seymour, 1977). The directional distribution is often conceptualized by a broad curve with a maximum energy (height) at the peak wave direction, decreasing with angular spread from the peak direction as shown in Figure 18 (Goda, 1985, Figure 2.12, page 30). A curve proportional to the cosine of direction squared, or higher power, is typically used to approximate the direction distribution. Near the frequency peak, a higher power is used to represent a narrower directional distribution typically found in the wave field. This concept of directional distribution of wave power in a wind wave field is used to account for restricted fetch conditions. The ACES method described above uses a weighted average of a fan of fetches to develop a single "effective restricted fetch" to use in the wave generation equations: The weighted average is based on the empirical directional distribution with selected power terms. The composite fetch method described below also uses this concept, but in a different manner.

Composite Fetch Method

The composite fetch method applies the SMB equations of the SPM method to an array of fetches, and then combines the resulting wave conditions for each fetch using a weighting function (Seymour, 1977; USACE, 1989). The method described by Seymour (1977) uses a cosine squared directional distribution and the Joint North Sea Wave Project (JONSWAP) frequency spectrum. The methodology was found to give good results when compared to field data in San Diego Bay, California and English Bay, Vancouver, Canada. The method described by USACE (1989) is a computer program called NARFET, and also uses the cosine based directional distribution. This formulation is based on data collected in sheltered waters including Puget Sound, Washington, and inland lakes. The primary advantage of the composite fetch method is that it allows a reasonable wave estimate for very irregular embayments, where large fetch areas exist in the primary wind direction.

The Composite Fetch Method was recently applied in an FIS at Sandy Point, Washington, which is in Puget Sound–Strait of Georgia sheltered waters (PWA, 2002). Figure 19 shows the site and the fan of fetches used in the analysis. Wave hind-casting for Sandy Point followed the methods outlined in the USACE Shore Protection Manual (1984) and the spectral contribution method using the JONSWAP spectrum (Seymour, 1977).

Figure 20 was the calculated spectrum for waves arriving from the northwest direction. Note that the spectrum was bimodal, with two peaks corresponding to 8 and 11 second period. The lower frequency peak resulted from the long, deep fetch up the Strait of Georgia (300 degrees on Figure 19), which was the primary wind direction used to develop this spectrum. The other frequency peak resulted from the remaining shorter fetches. While the frequency spectra were not used for subsequent analysis, a range of wave periods were employed, consistent with the two peaks.

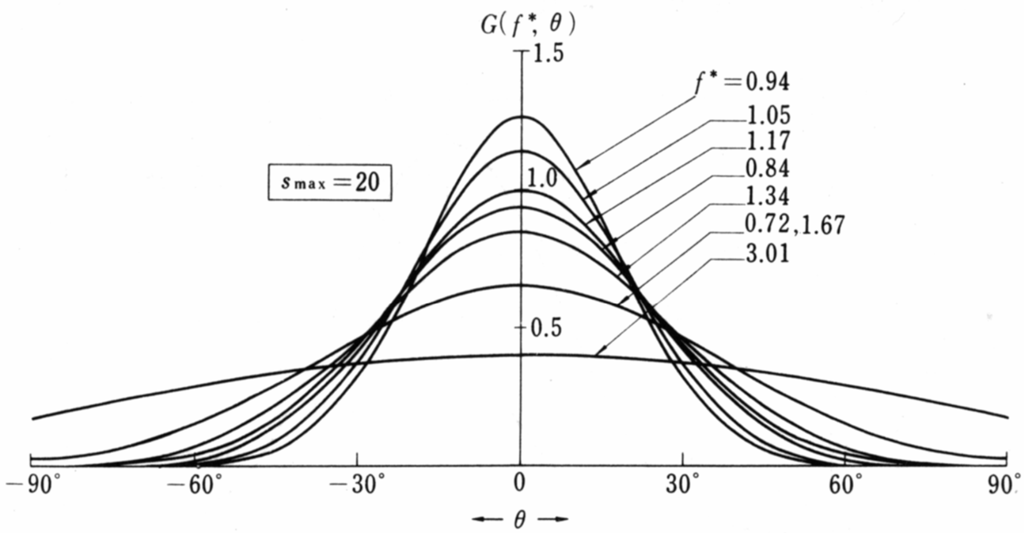

Fig. 2.12 Example of Mitsuyasu-type spreading function for s_{max}=20.

Figure 18. An example of a spreading function.

(Source: Figure 2.12, Random Sea and Design of Maritime Structues, Y. Goda, 1985)

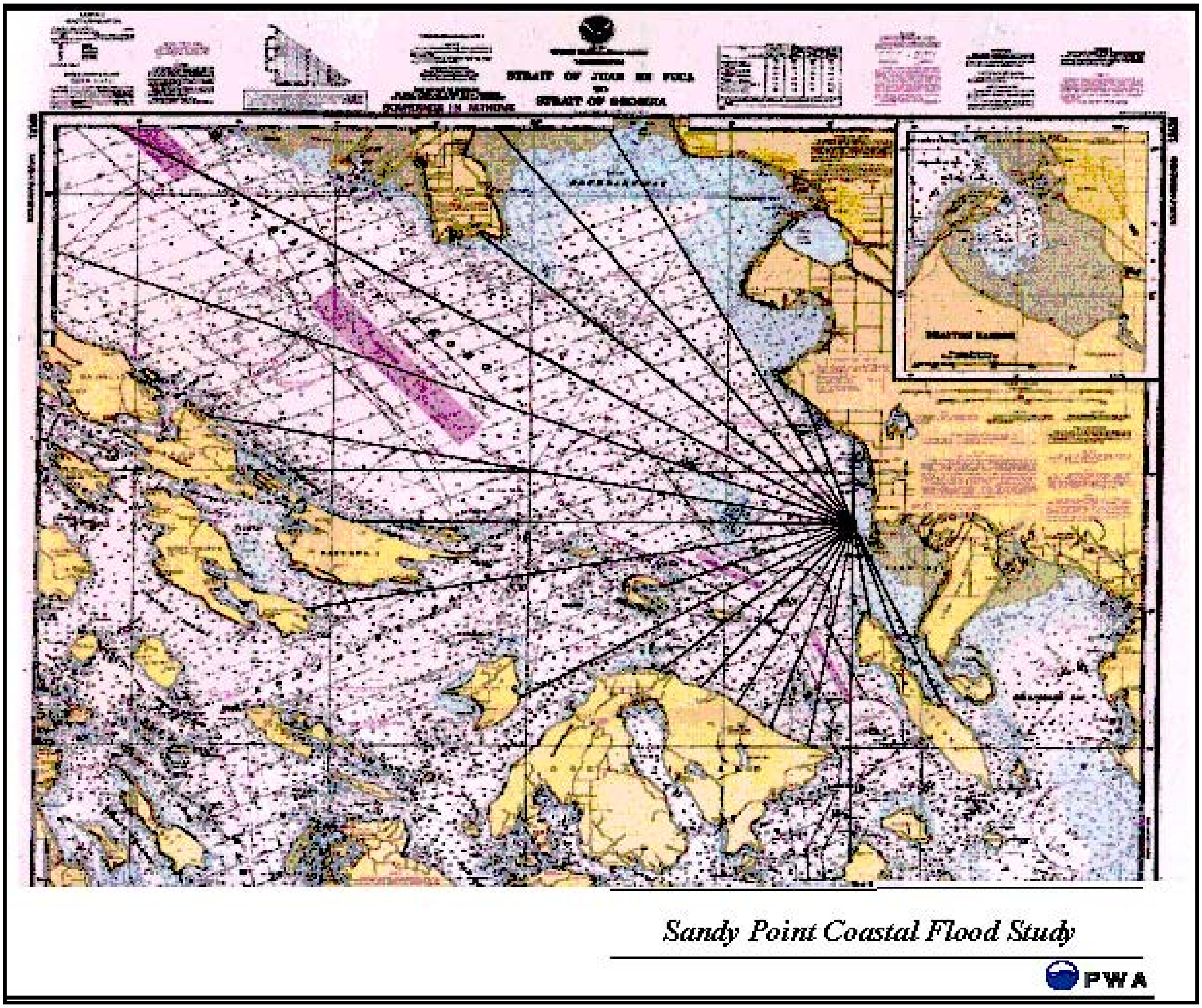

Figure 19. Composite fetch method application at Sandy Point, WA.

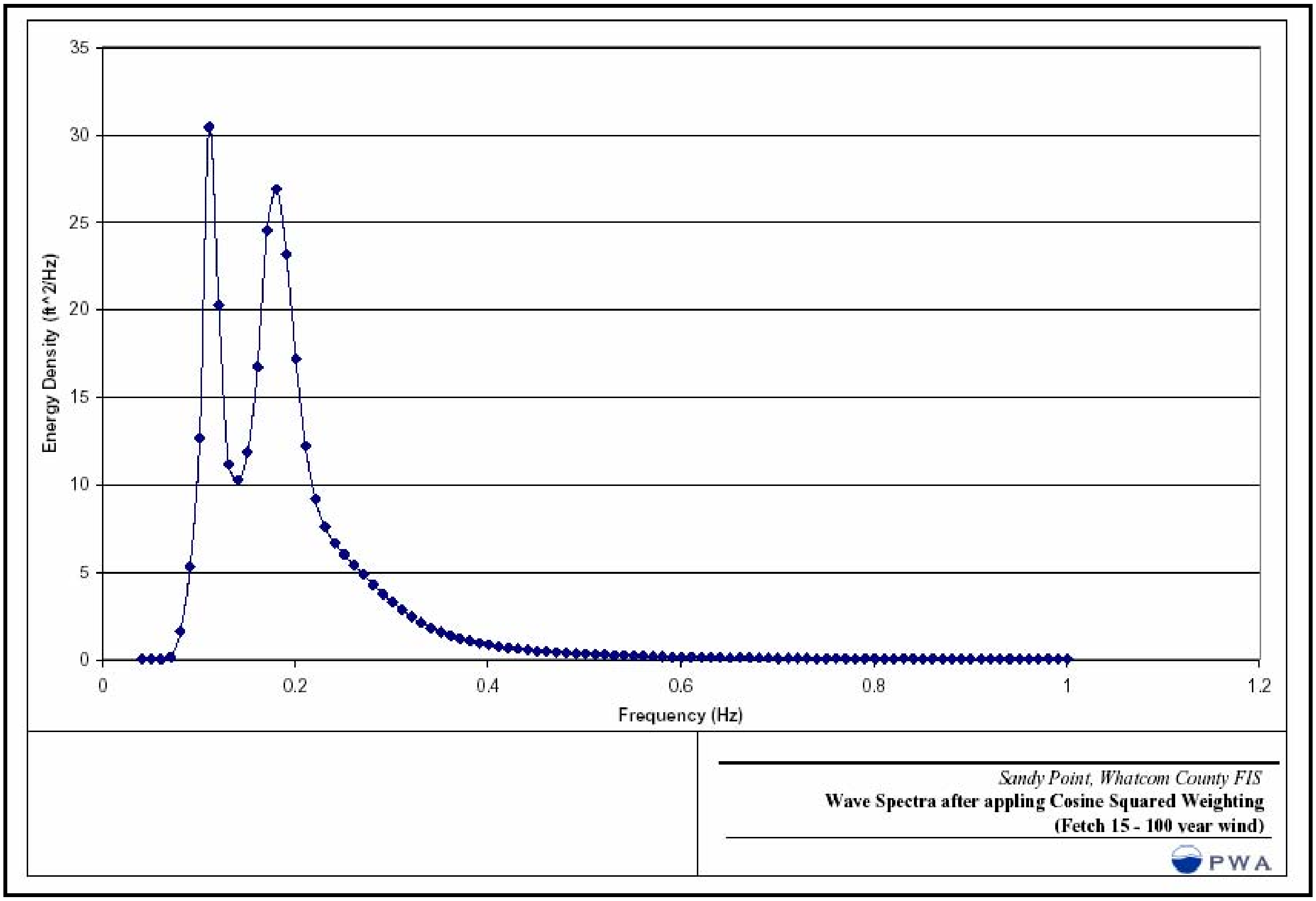

Figure 20. Bimodal wave spectra.

Changes in CEM (2003) compared to SPM (1984)

CEM suggests that where possible numerical models (e.g., Third Generation, Spectral Energy Models (SEMs)) should be used instead of the parametric models (Empirical Prediction Models). However, for shorter fetch lengths and simple situations where project costs would be minimal, CEM suggests the use of ACES program version of the parametric models (Called ACES Method herein). CEM also provides the Empirical Prediction Models similar to the SPM. Wind speeds in the equations are represented as friction velocities in the CEM, as opposed to wind stress factors in the SPM (1984). The CEM methods are described in Demirbilek et al. (1993). CEM and SPM methods are slightly different but results are expected to be comparable (Resio D. personal communication, 2004). Nomographs are also provided in the CEM, which states that these can be obtained using ACES more expediently.

The CEM recommends the use the deepwater wave growth formulae for all depths, including shallow water with the constraint that no wave period can grow past a limiting value for a given depth (Vincent 1985). This is a significant deviation from the SPM, which included different equations for shallow waters. This revisions result from studies by Bouws et al. (1985) and others. Interestingly, these studies indicate that the wave growth in shallow water is not dependent on the type of bottom sediment, but rather on the depth. A memorandum comparing the SPM and CEM methods have been prepared by Dewberry and Davis, LLC (2004) identifies the changes to wind-wave generation methods. The effect on results (calculated wave heights and periods) in FEMA flood studies should be evaluated before adopting the CEM changes.

An evaluation of the CEM method vs. the SPM method in shallow sheltered water areas would involve a comparison of the wave heights using both methods. An existing flood study (e.g., Sandy Point) can be used for the comparison because wind wave generation results based on the SPM method are already available. Testing can be accomplished in Phase 2 of this project.

New Procedures – Spectral Energy Models

The spectral energy models are two-dimensional, computer-assisted numerical routines that use wave growth and decay (dissipation) terms to represent energy sources and sinks in the wave action balance or energy equations. These are also called third-generation wave models. The computer model packages listed below are capable of generation and transformation of waves. There may be several other similar third-generation wave models that are compatible and mentioning a few of the models as examples below does not endorse these codes to be superior to the others. An added benefit of using the third-generation models is that output can include a wave spectra useful as input into other spectral wave models that need the detailed spectra.

SWAN

SWAN is a numerical wave model used to obtain realistic estimates of wave parameters in coastal areas, lakes, and estuaries from given wind, bottom, and current conditions (SWAN user manual). The model represents the following generation and dissipation processes:

- Generation by wind
- Dissipation by white capping
- Dissipation by depth induced breaking
- Dissipation by bottom friction
- Wave-wave interactions
- Obstacles

The model is free and is widely used today but is not pre-approved by FEMA for flood studies. Recent investigation of wave growth and decay in the SWAN model shows good comparisons with measured data for limited fetch conditions in wind wave frequency ranges (Rogers et. al., 2002; Boil et. al., 1999). See Figure 21 (Fig.7 extracted from Rogers et. al., 2002). The model was applied to Lake Michigan and the Mississippi Bight, and "tuning" of the model is discussed. It is important to compare these two-dimensional models with the other approved models and measured data to evaluate the merits or de-merits of the models.

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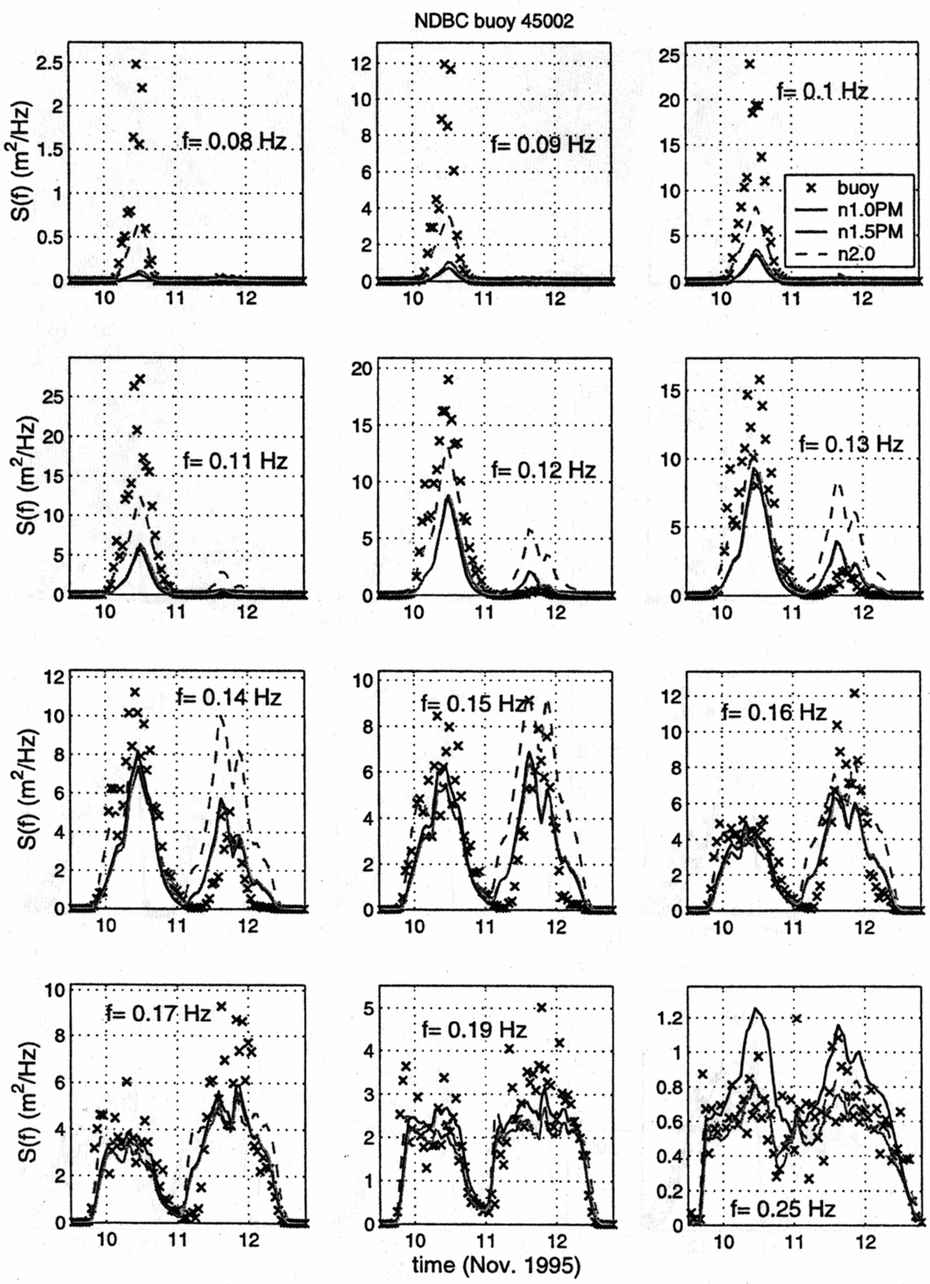

FIG. 7. Lake Michigan time series of frequency spectra at two NDBC buoy locations. The SWAN models are compared with measurements. The n1.0PM,NDS model is not included in this comparison, because it is practically identical to the n1.0PM model in this simulation: (a) NDBC buoy 45002 and (b) NDBC buoy 45007.

Figure 21. A sample comparison of SWAN Model results with measured data.

(Source: Journal of Physical Oceanography, Rogers, et al., 2002)

STWAVE

STWAVE is a steady-state wave transformation model that can include wind input and model wave growth. This model is widely used in USACE studies and has been used in small enclosed basins for wave generations and validated with the benchmarking system through a joint effort with Delft University of Technology, Delft, The Netherlands. Results are documented in voluminous comparisons on the Office of Naval Research (ONR) testbed project (testbed is discussed in the International Conference on Coastal Engineering [ICCE] 2002 proceedings, Smith, 2000, 2004).

Bottom friction is not implemented since there is little data for validation (Smith, personal communications, 2004). Unless propagation takes place over long distances in intermediate to shallow water, bottom friction may not be significant and STWAVE could still be used. However, Dally (personal communications) has measured surprisingly large damping over hard bottom (reefs), and to a lesser degree, sandy bottoms. In a very shallow basin bottom friction is potentially more important (say for propagation onto broad tidal flats) and STWAVE should be used with caution (see the Wave Transformations Focus Study Report).

MIKE 21 OSW

(following excerpts from http://www.dhisoftware.com/mike21/News/MIKE_21_OSW.htm):

> "MIKE 21 OSW is a fully spectral wind-wave model, which describes the propagation, growth and decay of short-period and short-crested waves in offshore areas. It includes wind generation, shoaling, refraction, wave breaking, bottom friction and wave-wave interaction. The output from the model consists of wave parameters including the significant wave height, peak wave period, average wave period, peak wave direction and mean wave direction."
>
> "Application of MIKE21 OSW in coastal areas (February 2001)"
>
> "Until recently Chi's fully spectral wind-wave model has mainly been used for large offshore areas and regional scale applications. New development and improvements have made the model also applicable in coastal and shallow water environment for various forcing conditions, see e.g. Johnson and Cooed-Hansen (J. Phys. Oceanogr., 30, pp. 1743-1756, 2000)."
>
> "In a recent paper wind-wave and air-sea interaction parameters were studied in two fetch-restricted coastal areas using the improved third-generation module in MIKE21 OSW. In the paper model results are compared with field data collected in water depth of 5 m (Femer Belt Model) and 7-10 m (Øresund Model)."
>
> "Recently, DHI has developed MIKE SW (not pre-approved by FEMA), which contains all the features of the MIKE OSW model but has a more flexible grid, making it more appropriate for deepwater to shallow water applications. MIKE NSW (approved by

FEMA) can also be used for wind wave generation and shallow water application, but this model is not a direct extension of MIKE OSW."

Theory

In the third-generation wave models (e.g., SWAN, STWAVE and MIKE OSW), the evolution of the wave spectrum is described by the spectral action balance equation. Wave growth and dissipation are accounted for by the source/sink terms, due to wind input, steepness and depth induced breaking and bottom friction. The equation solves the wave propagation in space and/or time and includes terms that represent frequency shifting and refraction due to variations in depth and currents. While STWAVE is stationary, SWAN and MIKE 21 OSW can be stationary or non-stationary (time dependent). The equations are solved on a forward marching technique over a finite difference grid.

Application

The models can be applied from deep to shallow water and for areas approximately in the range of 25–40 km (Although it can be applied to larger regions, the numerical scheme works better for mid-sized to smaller regions). The input data generally required to run the models are bathymetry, boundary conditions, wave spectra at the boundary (if any), wind speed and direction (one speed and direction for the stationary case). The output would be wave parameters (wave height, period and direction) and spectra at user selected grid points. Optionally other input (current, surge etc.) and output (wave setup etc.) are available depending on the model type. *G&S* could also include methods of converting data into usable input formats and also converting output into input needed in the other models for wave runup and setup.

The above third-generation models are widely used for wave generation in restricted fetches and sheltered water for design purposes but applications in FEMA Flood studies are not seen in the literature. Most of the applications in the literature are for validation and verification of the models using experimental measured data, or for tuning of model parameters. Some of the relevant applications of the SWAN model in the literature are at Lake Michigan and Mississippi Bight, (Rogers et al., 2002), partially enclosed basin between isles of Raasay and Isle of Skye, Lake George, Australia (Booij et al., 1999; Ris et al, 1999) and at Dutch Lake Ijssel, (Bottema et. al. 2003).

STWAVE has been applied in small enclosed basins for wave generations and validated with the benchmarking system through a joint effort with Delft. Results are documented in voluminous comparisons on the ONR testbed project (testbed is discussed in the ICCE 2002 proceedings, Smith, 2000, 2004)

Even with all the above testing, it is not clear how the results from SEMs differ from the parametric models traditionally used in FEMA flood studies, and in particular with extreme winds and waves.

Guidance with Wind Input

The above models are well documented in the respective user manuals. Wind speed and direction are important input parameters in the wave generation process and their usage in the models can vary from a simple uniform stationary wind field to a time and space varying wind field (in speed and direction) in the non-stationary modules. In the case of a flood study, the extreme event wind speed is parameterized as a single wind speed. Selection and conversion of wind data to model input needs guidance. Adequate guidance was not found in the literature, and therefore needs to be researched.

The wind input into non-stationary models is in the form of a time series. The other alternative is to run the model in stationary mode with a constant wind speed and direction. The assumption that waves have reached a steady state is implicit with this approach. This assumption is valid if the storm system lasts until the waves reach the maximum wave height for a given wind speed (fetch limited). Guidance is needed on using stationary vs. non-stationary modules.

Uncertainty – Need to Evaluate Further

Comparisons of simplified methods with the third-generation 2-D models are scarcely known although the third-generation model validations with wave measurements are ubiquitous in the literature. CEM (2003) recommends the third-generation models in design and planning situations and in most circumstances instead of the parametric models. Therefore a comparison of parametric methods (ACES, SPM, etc.) and the third-generation 2-D models is necessary as a baseline to continue using parametric methods and also for introducing 2-D models as an alternate method of wind wave generation for FEMA FIS. As a test case, the results from parametric methods and 2-D models can be compared with the measured data from an extreme event. The test cases also would help in defining wind input parameters for the 2-D models. An existing flood study site or an alternate site can be selected for testing. An existing flood study site would allow use of prior calculations and results.

2.4.5 Recommendations

Recommended improvements are:

- Write *G&S* for sheltered waters as part of the new *G&S* for the Pacific Coast geographic area, and include as an update to the existing *G&S* for the Gulf and Atlantic Coasts (could also be used for the Great Lakes geographic area, but this is not included in the present study);

- Update the existing language to be consistent with the USACE CEM. Specifically, evaluate the guidance in the CEM for revisions and clarify applications in FEMA studies. A focused study to compare results using CEM procedures to results using SPM procedures is recommended. An available FIS site or an alternative location can be selected for testing. Use of an available FIS site could simplify the study, if prior results and calculations are available, although the scope and purpose of the comparison should be clearly stated. The Sandy Point FIS is recommended because PWA recently completed this work and is familiar with the data and results;

- Describe a range of procedures that could be employed, as appropriate:
  - Existing Parametric Models Guidance, for Restricted Fetches, updated for CEM;
  - Enhanced Parametric Models, using the Composite Fetch Method recently employed in West Coast Sheltered Waters FISs;
  - Contemporary computer-assisted Spectral Energy Models (SEMs).
- A focused study to compare results from the SEMs and traditional Parametric Models, using restricted fetch methods. Application procedures for the SEMs would be clarified, specifically wind field definition.

2.4.6 Preliminary Time Estimates for Guideline Preparation

The Recommendations can be applied in about 400 to 500 person-hours, and in about 3 months elapsed time. Another 100 hours is recommended to allow participation of a technical review/steering committee, to be comprised of management and technical leaders presently working on the *G&S* review. Additional elapsed time to complete work may be needed to accomplish appropriate review and oversight: This indicates a 4-month timeframe is most appropriate. This estimate is based on use of the Sandy Point FIS data, which included all input data and results of the Parametric Model using Enhanced Composite Fetch Methods. Approximately, another 100 to 200 person-hours would be needed for additional analysis, if an alternate site is selected for testing. This estimate is for the analysis and report only. Review time for technical and institutional quality control is not included. These estimates are summarized in Table 2 at the end of this report.

2.4.7 Related Available and Important Topics if Any

Wave Transformations Focused Study, Study Topic 8: Swell and seas originating in the open ocean can penetrate coastal inlets, and may control coastal flood risk near the mouths of sheltered waters.

Wave Transformations Focused Study, Study Topic 9: Bottom friction factor used for very shallow waters may affect wind wave generation.

Storm Surge and wind setup may affect depths to the extent that wind wave generation is affected.

3 AVAILABLE TOPIC

3.1 WAVE DEFINITION- ATLANTIC/GULF AND PACIFIC (TOPIC 1)

3.1.1 Description of the Topic and Suggested Improvement

Matrix summary of need for Topic 1: Definitions of wave types using contemporary terminology and standardize the terminology.

The scope of this effort required that the focus report include definitions of wave types (swell, sea, storm, tsunami, etc.) and representative wave parameters such as significant wave height, controlling wave height for use in the Coastal Guidelines. The definitions are intended to provide descriptions of the storm wave characteristics in both the time domain and the spectral frequency domain. The research and review for this task required review of definitions presented in existing published materials, such as USACE Coastal and Hydraulics Lab (Coastal Engineering Manual), NOAA, and other national and international literature sources.

The reason this was considered a topic for further exploration is based on the Workshop 1 assessment that FEMA should have a glossary of wave terminology with definitions. The glossary would provide terminology related to commonly applied FEMA storm and wave characteristics and include other terms and notations that may be unfamiliar to those using or reviewing FEMA coastal flood study methodologies and techniques or coastal engineering in general.

The addition to the *G&S* of a direct link to a common resource for terminology would be useful for Study Contractors. To enhance Flood Mapping Partners ability to correctly use and understand the terminology of the coastal environment and physical processes that affect hazard assessment, Appendix D should require a specific section dedicated to providing the best available definition of this unique terminology.

The following was proposed for consideration and inclusion in Appendix D:

- Recommend the adoption of commonly used wave and hazard related terms encountered in the coastal environment (offshore and onshore). The following primary resources for inclusion in this task of the Storm Wave Characteristics Focus Study are:

    - Incorporate and refine the specific "Glossary of Coastal Terminology" from the CEM. It is comprehensive and ties in with past practices of FEMA reliance on the USACE as a Federal partner for assistance on coastal technical matters.

    - Incorporate entirely, the five listings of notations and parameters in the January 1986 publication from the International Association for Hydraulic Research titled, “List of Sea State Parameters.” These include:

(1) basic notations,
(2) general parameters and functions,
(3) standard parameters and functions,
(4) directional parameters and functions, and
(5) supplementary parameters and functions.

- A more significant and important task for this Focused Study group would be to provide specific guidance on how these terms relate to each other and should be applied relative to the following:

  - FEMA guidance for coastal flood studies,
  - Physical processes that are directly associated with FEMA coastal hazard assessments and flood mapping, and
  - Required coastal hazard study methodologies, techniques and models.

3.1.2 Confirm Availability

Both the CEM and the IAHR lists are available for immediate use. Wherever possible in development of the guidance as a digital document, a link to these resources would be important in each section of the guidance.

3.1.3 Preliminary Time Estimates for Guideline Improvement Preparation

Table 2 at the end of this document summarizes the preliminary Time Estimates for the Wave definition topic.

3.2 WAVE GENERATION IN SHELTERED WATER–ATLANTIC/GULF COASTS

3.2.1 Description of the Topic and Suggested Improvement

The current practice is to apply the parametric models using the straight line fetch method (USACE SPM, 1984), restricted fetch method, or ACES program to generate the wave conditions at the site of interest. The wind-speed inputs into these methods are 60 mph for Northeaster-dominated areas (Northern Atlantic), and 80 mph for hurricane-dominated areas. The appropriateness of these wind conditions should be analyzed based on more recent information, and new guidelines should be provided for wind input selection. Also, the *G&S* should be clarified as to whether CEM and or SPM methods are to be employed.

The *G&S* for the Great Lakes and Gulf and Atlantic geographic areas are slightly out of date but functional. A suggested improvement is to update these based on the new version of the Pacific Coast *G&S*.

3.2.2 Confirm Availability

The current wind speeds adopted in FEMA FIS were suggested by the National Academy of Sciences (NAS 1977). These can be evaluated against more recent results from extremal analyses that are based on measured extreme wind speeds (see for e.g., National Hurricane Center web site, http://www.nhc.noaa.gov/HAW2/pdf/cat1.pdf). This and other available literature can be used to update guidance on wind speeds to be used in the event that wind data are not available for a particular FIS site. In simple terms, the currently used wind speeds could be increased to represent a higher category hurricane (e.g., Category 3 instead of category 1, etc.) that represents a 100-year return period wind speed.

The USACE CEM is readily available and in use. Required adjustments to update from the SPM to the CEM for the restricted fetch method are minimal. It is presumed that the guidance in the USACE CEM is sound, but implications to results for FEMA applications should be evaluated prior to use.

3.2.3. Preliminary Time Estimates for Guideline Preparation

To develop guidelines for the Atlantic and Gulf Coasts, based on Pacific Coast *G&S* and additional research, about 60 hours will be required.

Table 2 at the end of this document summarizes the preliminary Time Estimate for this topic.

4 ADDITIONAL OBSERVATIONS

The special case for hurricane-induced storm seas in sheltered waters has not been addressed, but may be important. There may be recent experiences, for example, Chesapeake Bay in 2003, from which observations and data can be used to evaluate the range of methods available.

The selection of waves for the open coast and sheltered water will be dependent on the methods chosen for analysis. Two methods are under consideration: the Events Selection Method and Response-Based Method. The first method is a deterministic method that selects a single large forcing event, while the second method is a statistical method that performs frequency analysis on the response events as the result of many large waves. In Phase 2, these concepts will be further developed.

5 SUMMARY

The Storm Wave Characteristics Focused Study group was charged with developing recommendations on wave definitions; conversion from SPM to CEM on shallow water waves; and available sea and swell databases for Atlantic /Gulf and Pacific Coasts; and local seas for Sheltered Water. The swell and wave information from offshore is necessary for wave transformation from deepwater to nearshore and definition of wave conditions for the 1%-annual-chance-flood-event.

5.1 CRITICAL TOPICS

This study lists and critically looks at several sources of wave and swell data and recommends the following:

- For the Pacific Coast, GROW data is recommended, but updated WIS data is under development and is expected to include input from GROW. After this work is completed WIS may be the database of choice for the Pacific Coast.
- For the Atlantic and Gulf Coasts, the WIS database is sufficient.

For the Pacific, further studies are necessary to critically examine the lack of bias in the databases, formulate a methodology to prepare input data for wave transformation, and develop a suitable matrix of GROW directional spectra to ensure complete coverage of the deep water wave properties envelope. About 200 hours will be required for the Pacific Coast to complete these tasks over 3 months duration.

For the Atlantic/Gulf Coasts, the following guidelines on the use of WIS databases are needed:

- extrapolation to 100 years;
- appropriateness of using either the 100-year significant wave height or 20-year maximum; and
- clarification on extrapolation to 100 years.

The measured directional spectra from CDIP buoys contain the contribution from local wind. The modeled nearshore swell estimates for the Southern California Bight do not contain the contribution from local wind. A study of the available nearshore buoy records will be made to assess whether inclusion of the local wind will make a significant change in the high frequency part of the spectrum (typically periods less than 9 seconds). If there are significant changes, then a separate database will be proposed for measured variations in the wind wave spectrum. The task will take approximately 120 hours.

Improvements to the *G&S* are recommended for Storm Wave Characteristics in Sheltered Waters for the Pacific Coast. Traditional methods are available and have been successfully applied in recent FISs. These traditional methods are based on SPM guidance, and need to be reconciled with revised guidance in the CEM. In addition, the traditional methods rely on parametric models while more sophisticated spectral analysis models are now available and are being used in the industry. Hence, the updates to the *G&S* should address whether the spectral analysis models are approved for FEMA FISs, and how they should be applied. Further analysis is necessary to better understand how the results of the revised and new methodologies would compare with results from the traditional methods. It is recommended that analysis be conducted prior to revising the *G&S*. The proposed analysis will generally consist of applying the revised and new methodologies to the same data set, reviewing the results, and noting key steps and factors affecting the results. The proposed analysis is estimated to take up to 600 person-hours over a 3-month duration. An additional 100 person-hours and 1-month duration is estimated for technical oversight and review. These estimates presume that the study will be applied to data already available, probably from a recently completed FIS (the Sandy Point FIS is proposed), and additional time and costs are expected if the analysis is applied to a new site. The recommendations for all critical topic is summarized in Table 1.

5.2 AVAILABLE TOPICS

Several sources of wave definitions have been identified, including CEM and IAHR, to assist in the creation of a comprehensive set of definitions for all coasts of the continental U.S. in the time and frequency domain. Two separate sets of standardized definitions, and a specific listing and definition of common notations will be created for Atlantic/Gulf and Pacific coasts. About 240 person-hours will be required for this effort.

It is suggested that the wave generation issues in the sheltered waters for the Atlantic and Gulf Coasts can be improved based on the Pacific Coast *G&S* and additional research on wind conditions based on measured wind speeds. This effort will take about 60 person-hours. The recommendations for all available topics is summarized in Table 1.

6 RECOMMENDATIONS

Table 1 is a summary of recommendations for Storm Wave Characteristics Critical Topics and Available Topics. Note that the focused study combined Topics 4 and 5, incorporated a portion of Topic 3 into Topics 4 and 5. Other elements of Topic 3 (e.g., wave runup and wave setup) were considered in other focused studies.

Table 3 Summary of Findings and Recommendations Storm Wave Characteristics

Topic Number	Topic	Coastal Area	Priority Class	Availability / Adequacy	Recommended Approach	Related Topics
4 and 5	Sea and Swell	AC	C	MIN	WIS database is recommended for use. Clarify extrapolation to 100-year; investigate appropriateness of using either 100-year significant wave height or 20-year maximum. Clarify use of equivalent deepwater wave - definition (Topic 1)	8, 9, 51
		GC	C	MIN		

Table 3 Summary of Findings and Recommendations Storm Wave Characteristics

Topic Number	Topic	Coastal Area	Priority Class	Availability / Adequacy	Recommended Approach	Related Topics
		PC	C	MAJ	1. GROW database is recommended for use in near term for swell and sea. Confirm lack of bias in GROW database. WIS can be used after completion of current revision. CDIP data can be used for model verification. 2. Develop *G&S* for preparation of input data for wave modification models based on GROW directional spectra. 3. Conduct a study of the available nearshore data for Southern California Bight to assess whether inclusion of the local wind will make a significant change in the high frequency part of the spectrum	
		SW	C	MAJ	Add guidance on use of Coastal Engineering Manual (CEM); conduct a focused study to confirm that Shore Protection Manual (SPM) results are similar (validation for previous studies). Conduct a focused study and describe procedures for: (1) existing parametric model guidance; (2) enhanced parametric models; (3) spectral energy models	6, 8, 9, 51
1	Wave Definitions	AC	A	Y	The recommended approach includes: (1) adopt the CEM "Glossary of Coastal Terminology" and International Association of Hydraulic Engineering and Research "List of Sea State Parameters" (for notations); and (2) clarify the correlation of these terms to the actual guidance and various methodologies to ensure consistency	4, 5, 50, 51
		GC	A	Y		
		PC	A	Y		
		SW	A	Y		
5	Local Sea - Guidelines for Local Sea	SW (Atl)	A	Y	The recommended approach is to update *G&S* based on Pacific Sheltered Water G &S.	6, 51

Table 3 Summary of Findings and Recommendations Storm Wave Characteristics						
Topic Number	Topic	Coastal Area	Priority Class	Availability / Adequacy	Recommended Approach	Related Topics

Key:
Coastal Area
AC = Atlantic Coast; GC = Gulf Coast; PC = Pacific Coast; SW = Sheltered Waters
Priority Class
C = critical; A = available; I = important; H = helpful
(Recommend priority italicized if focused study recommended a change in priority class)
Availability/Adequacy
"Critical" Items: MIN = needed revisions are relatively minor; MAJ = needed revisions are major
"Available" Items: Y = availability confirmed; N = data or methods are not readily available
"Important" Items: PRO = procedures or methods must be developed; DAT = new data are required;
PRODAT = both new procedures and data are required

Table 4 Preliminary Time Estimate for Guideline Improvement Preparation		
Topic Number	Item	Time (Hours)
Swell and Sea- Pacific Coast		
4 & 5	Review GROW Publication	40
	Develop and define techniques for input format for wave modification models	80
	Prepare description of interface process	40
	Coordinate with WIS Pacific Coast Revisions	40
	TOTAL	200
Offshore Wave Data-Atlantic/Gulf		
4 & 5	Investigate 100-year significant wave height or 20-year max.	60
	Clarify use of equivalent deep water condition	40
	Clarify extrapolation to 100-year	20
	TOTAL	120
Wind waves in Southern California Bight		
5	Evaluate error in nearshore wave data with respect to local sea	90
	Recommend an approach	30
	TOTAL	120
Wave Generation in Sheltered Waters-Pacific		
5	Write *G&S* for sheltered water and include as an update to the existing *G&S* for Gulf and Atlantic Coasts. Describe a range of procedures that could be employed.	100
	Compare CEM and SPM procedures using a case study (an existing FIS site) and clarify application of CEM in FEMA studies	100
	A focused study to compare SEMs and traditional parametric models using restricted fetch methods. Application procedure for SEMs including wind field definition	300
	Allow participation of a technical review	100
	TOTAL	600
Guideline Preparation-Pacific Coast		

Table 4 Preliminary Time Estimate for Guideline Improvement Preparation		
Topic Number	Item	Time (Hours)
1	Using the compiled glossary of terms and notations (from CHL and IAHR sources), correlate each of key terms with the coastal methodologies and application.	80
	Prepare for application within Appendix D	80
	Prepare for application for Pacific Coast Guidelines	80
	TOTAL	240
Wave Generation in Sheltered Water-Atlantic/Gulf		
5	Develop Guidelines based on Pacific Coast	60
	TOTAL	60

7 REFERENCES

Booij N, R.C. Ris, and L.H. Holthuijsen. 1999. A Third-Generation Wave Model for Coastal Regions – 1: Model Description and Validation. *Journal of Geophysical Research-Oceans* 104(C4):7649–7666.

Bottema, M., J.P. de Waal, and E.J. Regeling. 2003. Some Applications of the Lake Ijssel/Lake Sloten Wave Data. Pages 413-425 in *Proceedings: 28th International Conference on Coastal Engineering*.

Bouws, E., H. Gunther, and C.L. Vincent. 1985. Similarity of Wind Spectrum in Finite-Depth Water, Part 1: Spectrum Form. *Journal of Geophysical Research* 85(C3):1524–1530.

Cardone, V.J. 1992. On the Structure of the Marine Surface Wind Field in Extratropical Storms. Pages 54-66 in *Preprints of the 3rd International Conference on Wave Hindcasting and Forecasting*, Montreal, Quebec, May 9-22, 1992. Published by Environment Canada. Downsview, Ontario.

Cardone, V.J., and B.T. Callahan. 1992. Kinematic Analysis of the Surface Wind Field in the Halloween Storm and a Preliminary Spectral Model Hindcast. Pages 101-118 in *Supplement of the 3rd International Conference on Wave Hindcasting and Forecasting*, Montreal, Quebec, May 9-22, 1992. Published by Environment Canada. Downsview, Ontario.

Cardone, V.J., A.T. Cox, and V.R. Swail. 1999. *Evaluation of NCEP Reanalysis Surface Marine Wind Fields for Ocean Wave Hindcasts*. CLIMAR 1999 Preprints. September 8-15, 1999, Vancouver, Canada.

———. 2000. Specification of the Global Wave Climate: Is This the Final Answer? *6th International Workshop on Wave Hindcasting and Forecasting*. November 6-10, 2000, Monterey, California.

Cardone, V.J., A.T. Cox, J.A. Greenwood, and E.F. Thompson. 1994. *Upgrade of Tropical Cyclone Surface Wind Field Model*. (Misc. Paper CERC-94-14.) U.S. Army Corps of Engineers.

Cardone, V.J., A.T. Cox, W.J. Pierson, W.B. Sylvester, W.L. Jones, and J. Zec. 1999. NASA Scatterometer High Resolution Winds for Hurricane Lili. *IEEE 1999 International Geoscience and Remote Sensing Symposium* (IGARRS'99) 28 June-2 July, 1999, Hamburg.

Cardone, V.J., H.C. Graber, R.E. Jensen, S. Hasselmann, and M.J. Caruso. 1995. In Search of the True Surface Wind Field in SWADE IOP-1: Ocean Wave Modelling Perspective. *The Global Atmosphere and Ocean System* 3:107-150.

Cardone, V.J., R.E. Jensen, D.T. Resio, V.R. Swail and A.T. Cox. 1996. Evaluation of Contemporary Ocean Wave Models in Rare Extreme Events: The "Halloween Storm" of October, 1991; and the "Storm of the Century" of March, 1993. *Journal of Atmospheric and Oceanic Technology* 13:198–230.

Cardone, V.J., and D.T. Resio. 1998. Assessment of Wave Modeling Technology. *Fifth International Workshop on Wave Hindcasting and Forecasting*. 26-30 January 1998. Melbourne, FL.

———. 1999 (January). Wave Climate Modeling. *Shore and Beach* 67(1).

CEDAS. 2001. *Coastal Engineering Design and Analysis System*, Version 1.0. Veri-Tech Inc., Vicksburg, MS.

Cox, A.T., and V.J. Cardone. 2000. Operational System for the Prediction of Tropical Cyclone Generated Winds and Waves. *6th International Workshop on Wave Hindcasting and Forecasting*. November 6-10, 2000, Monterey, CA.

Cox, A.T., V.J. Cardone, and V.R. Swail. 1998. Evaluation NCEP/NCAR Reanalysis Project Marine Surface Wind Products for a Long Term North Atlantic Wave Hindcast *Fifth International Workshop on Wave Hindcasting and Forecasting*. January 26-30, 1998. Melbourne, FL.

Cox, A.T., and V.R. Swail. 2001 (February). A Global Wave Hindcast over the Period 1958-1997: Validation and Climate Assessment. *Journal of Geophysical Research-Oceans* 106(C2):2313–2329.

Cox, A.T., V.J. Cardone, and V.R. Swail. 1999. *On the Use of In-Situ and Satellite Wave Measurements for Evaluation of Wave Hindcasts*. CLIMAR 1999 Preprints. September 8-15, 1999, Vancouver, Canada.

Cox, A.T., J.A. Greenwood, V.J. Cardone, and V.R. Swail. 1995. An Interactive Objective Kinematic Analysis System. *Fourth International Workshop on Wave Hindcasting and Forecasting*. October 16–20, 1995. Banff, Alberta, Canada.

Demirbilek Z., S.M. Bratos, and E.F. Thompson. 1993. *Wind Products for Use in Coastal Wave and Surge Models*. (Miscellaneous Paper, CERC-93-7.) U.S. Army Engineer Waterways Experiment Station. Vicksburg, MS.

Dewberry & Davis, LLC. 2004 (January 23). *Coastal Engineering Manual vs. Shore Protection Manual: An Overview and List of Recommendations for Improving Existing FEMA Coastal Hazard Analysis Methodologie*s. (For Use and Consideration in the Guidelines Project Focus Studies).

Federal Emergency Management Agency (FEMA). 1995 (March). *Guidelines and Specification for Wave Elevation Determination and V Zone Mapping*. National Flood Insurance Program, Mitigation Directorate, Federal Insurance Administration. Final draft. Available <http://www.fema.gov/mit/tsd/DL_VZn.htm>.

Goda Y. 1985. *Random Seas and Design of Maritime Structures*. University of Tokyo Press, Tokyo, Japan.

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmannm and P.A.E.M. Janssen. 1994. *Dynamics and Modelling of Ocean Waves*. Cambridge University Press.

Kushnir, Y., V.J. Cardone, J.G. Greenwood, and M.A. Cane. On the Recent Increase in North Atlantic Wave Heights. *Journal of Climate* 10:2107–2113.

Lima, Jose A.M., V.J. Cardone, T.M. Mitchell, M.J.Vogel, and A.M. Scofano. 2001. Wave and Wind Hindcast Study for Southeast Brazil. *Proceesings of OMAE 2001 20th International Conference on Offshore Mechanics and Arctic Engineering*, June 3-8 2001, Rio de Janeiro, Brazil.

Meteorology and Oceanography Center, MTS. 2001 Conference Proceedings (available from Marine Technology Society, 1828 L St., N.W., Suite 906, Washington, DC 20036).

Meteorology International, Inc. (MII). 1977. *Deep Water Wave Statistics for the California Coast*. Department of Navigation and Ocean Development.

MIKE 21 OSW. http://www.dhisoftware.com/mike21/News/MIKE_21_OSW.htm

National Academy of Sciences. 1977. *Methodology for Calculating Wave Action Effects Associated with Storm Surges*. Washington, DC.

Resio, D.T., V.R. Swail, R.E. Jensen, and V.J. Cardone. 1999. Wind Speed Scaling in Fully-Developed Seas. *Journal of Physical Oceanography* 29(8):1801–1811.

Ris, R.C., L.H. Holthuijsen, and N. Booij. 1999. A Third-Generation Wave Model for Coastal Regions – 2: Verification. *Journal of Geophysical Research-Oceans* 104(C4):7667–7681.

Rogers, W.E., P.A. Hwang, and D.W. Wang. 2002. Investigation of Wave Growth and Decay in the SWAN Model: Three Regional-Scale Applications. *Journal of Physical Oceanography* (33):366–389.

Seymour, R.J. 1977. Estimating Wave Generation on Restricted Fetches. *Journal of Waterway, Port, Coastal, and Ocean Engineering* pp.251–264.

Smith, J.M. 2000. Wave Hindcasting and Forecasting Conference in 2000.

Swail, V.K., V.J. Cardone, and B. Eid. 1991. Extreme Wave Climate off the West Coast of Canada. *Preprint Volume of the AMS Conference on Meteorology and Oceanography of the Coastal Zone*. May 6-10, 1991, Key Biscayne, FL.

———. 1992. An Extremes Wind and Wave Hindcast off the West Coast of Canada. *Preprints of the 3RD International Conference on Wave Hindcasting and Forecasting*, Montreal, Quebec, May 9-22, 1992; 339-350. Published by Environment Canada, Downsview, Ontario.

Swail, V.R., and A.T. Cox. 2000. On the Use of NCEP/NCAR Reanalysis Surface Marine Wind Fields for a Long Term North Atlantic Wave Hindcast. *Journal of Atmospheric Technology* 17(4):532–545.

Swail, V.R., A.T. Cox, and V.J. Cardone. 1999. *Analysis of Wave Climate Trends and Variability*. CLIMAR 1999 Preprints. September 8-15, 1999, Vancouver, Canada.*

———. 1999. Trends and Potential Biases in NCEP-Driven Ocean Wave Hindcasts. *2nd Conference on Reanalysis*. Redding, UK.

Swail, V.R., E.A. Ceccacci, and A.T. Cox. 2000. The AES40 North Atlantic Wave Reanalysis: Validation and Climate Assessment. *6th International Workshop on Wave Hindcasting and Forecasting*. November 6-10, 2000, Monterey, California.

Swail, V.R., V.J. Cardone and A.T. Cox. 1998. A Long Term North Atlantic Wave Hindcast *Fifth International Workshop on Wave Hindcasting and Forecasting*. January 26-30, 1998. Melbourne, FL.

SWAN User Manual, 2003. SWAN Cycle III version 40.20, May 2003.

Tetra Tech, Inc. 1982. *Methodology for Computing Coastal Flood Statistics in Southern California*. (Report TC-3205.)

Tillotson, K., and P.D. Komar. 1997. The Wave Climate of the Pacific Northwest (Oregon and Washington): A Comparison of Data Sources. *Journal of Coastal Research* 13(2):440–452.

Tolman, H.L. 1989. The Numerical Model WAVEWATCH: a Third-Generation Model for the Hindcasting of Wind Waves on Tides in Shelf Seas. *Communications on Hydraulic and Geotechnical Engineering*, Delft Univ. of Techn., ISSN 0169-6548, Rep. no. 89-2.

———. 1991. A Third-Generation Model for Wind Waves on Slowly Varying, Unsteady and Inhomogeneous Depths and Currents. *Journal of Physical Oceanography* 21:782–797.

———. 1992. Effects of Numerics on the Physics in a Third-Generation Wind-Wave Model. *Journal of Physical Oceanography* 22:1095–1111.

———. 1995. *On the Selection of Propagation Schemes for a Spectral Wind Wave Model*. (NWS/NCEP Office Note 411.)

———. *User Manual and System Documentation of WAVEWATCH-III Version 1.15.* (NOAA/NWS/NCEP/OMB Technical Note 151.)

———. 1999a. *User Manual and System Documentation of WAVEWATCH-III Version 1.18*. (NOAA/NWS/NCEP/OMB Technical Note 166.)

———. 1999b. *WAVEWATCH-III Version 1.18: Generating GRIB Files*. (NOAA/NWS/NCEP/OMB Technical Note 167.)

———. 1999c. *WAVEWATCH-III Version 1.18: Post-Processing Using NCAR Graphics*. (NOAA/NWS/NCEP/OMB Technical Note 168.)

Tolman, H.L., and N. Booij. 1998. Modeling Wind Waves Using Wavenumber-Direction Spectra and a Variable Wavenumber Grid. *The Global Atmosphere and Ocean System* 6:295–309.

Tolman, H.L., and D. Chalikov. 1996. Source Terms in a Third-Generation Wind-Wave Model. *Journal of Physical Oceanography* 26:2497–2518.

U.S. Army Corps of Engineers. 1984. *Shore Protection Manual*. Waterways Experiment Station. Vicksburg, MS.

———. 1989. *NARFET–Wind-Wave Generation on Restricted Fetches*. (Coastal Engineering Technical Note 1-4 3/89.)

———. 1992. *ACES 1.07*. Waterways Experiment Station. Vicksburg, MS.

———. 2001. *Coastal Engineering Manual*. Part 11. Chapter 4. p.11-4-11.

———. 2003 (July). Coastal Engineering Manual. *Part 2, Chapter 2, Meteorology and Wave Climate*.

———. 2003. *Encinitas and Solana Beach Shoreline Feasibility Study, without Project Conditions*. Coastal Engineering Appendix. Prepared for Los Angeles District, prepared by Noble Consultants, Inc.

Vincent C.L. 1985. Depth-Controlled Wave Height. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 111(3):459–475.

WAM Development and Implementation Group (WAMDI Group). 1988. The WAM Model-A Third Generation Ocean Wave Prediction Model. *Journal of Physical Oceanography* 18:1775–1810.

Wittmann, P.A. 2001. Implementation of WAVEWATCH III at Fleet Numerical Meteorology and Oceanography Center. *Oceans 2001 MTS/IEEE Conference Proceedings* (available from The Marine Technology Society, 1828 L Street, N.W., Suite 906 Washington, DC 20035).