D.4.4 Waves and Water Levels

This section provides guidance for two study components: the definition of offshore waves and their transformation to the surf zone; and the determination of water levels, including tide and wind setup. Guidance on special considerations in sheltered waters is provided for both of these components. This section also includes guidance on water level during El Niños, 1% still water levels (SWLs), combined effects of surge and riverine runoff, and consideration of non-stationary processes.

D.4.4.1 Waves

Section D.4.2 defines the analysis steps of a typical Flood Insurance Study (FIS) in terms of zones moving from the offshore zone to the shoaling zone to the surf zone to the backshore. The characteristics of waves at the surf zone must be defined to estimate runup, setup, and overtopping (see Section D.4.5), erosion (see Section D.4.6), and effects on coastal structures (see Section D.4.7) at the shore. Wave characteristics at the surf zone are seldom available directly from measurements. Therefore, typical steps in the wave analysis for a FIS include defining wave characteristics in the offshore zone, transforming the waves to the surf zone, and then creating equivalent deepwater water characteristics (back-transforming), so the transformed characteristics can be easily used in subsequent analyses.

The primary source of offshore wave information consists of predictions from wave hindcasting models, supported by limited measurements. The hindcast databases have been extended to cover relatively long periods (30 years or more), while measurements are generally available for only a few years and are sparsely spaced. Hindcasts and observations commonly represent conditions at a point offshore, usually in deep water. Because waves in the surf zone are strongly influenced by local bathymetry and shoreline configuration, hindcast or measured wave data must be modified to account for wave transformations between the reference station and the study area.

The guidance provided below on wave analysis includes the following:

- Definition of wave spectra (D.4.4.1.1), which represent the distribution of wave energy over frequencies and directions, and are used in some wave transformations;

- Discussion of deepwater wave data (D.4.4.1.2), which may be used where available to define offshore wave characteristics;

- Discussion of hindcast offshore wave data (D.4.4.1.3), which are considered the most likely sources of wave characteristics for FISs on the open coast;

- Description of wave transformations (D.4.4.1.4), with emphasis on spectral transformation methods and a discussion of potential regional approaches to spectral transformations; and

- Description of special considerations in sheltered waters (D.4.4.1.5), where wave generation is dependent on local winds, and offshore waves are typically determined using wave hindcasts, which are often fetch-limited.

Because it typically occurs in the backshore zone, wave overland propagation and dissipation is treated in Section D.4.5, Wave Setup, Runup, and Overtopping.

Several general methods of defining offshore waves and transforming them to the surf zone with varying complexity are described here; the methods selected in a particular study area will depend on the availability of information and the complexity of shoaling zone and surf zone characteristics. It is difficult to define a single method for a given setting – judgment is required by the Mapping Partner to select the type and level of analysis appropriate to the setting and study needs. A general consideration is that the level of wave analysis should be appropriate to support the methods to be used in subsequent analysis of wave effects at the shoreline.

D.4.4.1.1 Wave Spectra

The characterization of random waves by *spectra* is summarized here. Wave spectra represent the distribution of wave energy over frequency and direction. Wave spectra can be either continuous or discrete and can be expressed either one-dimensionally or two-dimensionally.

A one-dimensional (1-D) continuous spectrum, $S(f)$, specifies the distribution of the wave energy over frequency, *f*, as shown schematically in Figure D.4.4-1a.

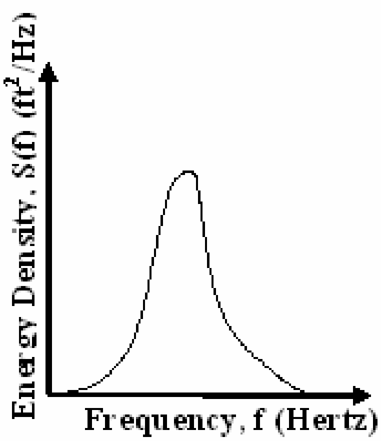

Figure D.4.4-1a) Example of a One-Dimensional Continuous Spectrum

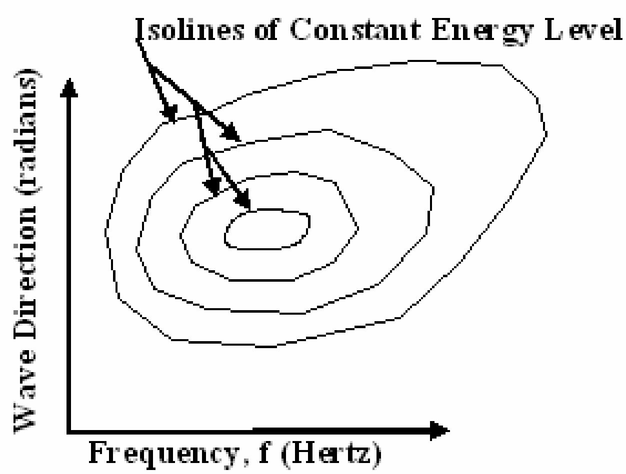

Figure D.4.4-1b) Example of a Two-Dimensional Continuous Energy Spectrum

The energy density contained in a small frequency interval, Δf, is approximately $S(f)\Delta f$; the integral over all frequencies is the total energy density of the waves, *E*, where:

$$E = \overline{\eta^2} = \int_0^\infty S(f)df \qquad \text{(D.4.4-1)}$$

is the mean square of the fluctuations of the water surface η about the mean level. The spectrum can also be two-dimensional (2-D), with the wave energy distributed over both wave direction and frequency as shown in Figure D.4.4-1b. A 2-D (or directional) wave energy spectrum is denoted as $S(f,\theta)$ in which θ is the direction from which the waves are arriving; that is, according to the usual convention, a north wind generates north waves. In this case, the energy density is the double integral over both direction and frequency:

$$E = \int_0^\infty \int_0^{2\pi} S(f,\theta) d\theta df \qquad \text{(D.4.4-2)}$$

such that the total energy at any frequency is the integral of the energy spectral density over direction at that frequency.

Wave spectra can also be discrete, and analogues exist between the expressions for discrete and continuous spectra. Figure D.4.4-2a shows an example of a 1-D discrete spectrum in which the total energy density is now given by a summation over a set of *N* discrete frequency components:

$$E = \sum_{n=1}^{N} S(f_n) \qquad \text{(D.4.4-3)}$$

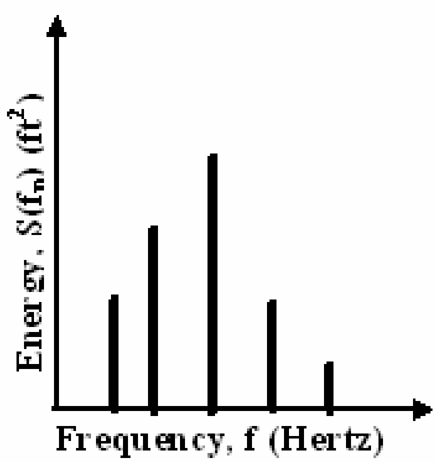

Figure D.4.4-2a) Example of One-Dimensional Discrete Spectrum

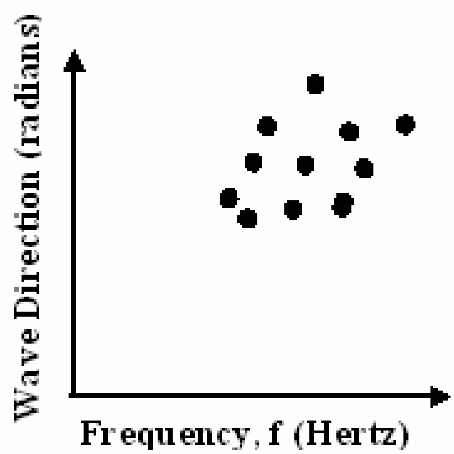

Figure 4.4-2b) Example of Two-Dimensional Discrete Spectrum

Similarly, the 2-D discrete spectrum, Figure D.4.4-2b, is denoted as $S(f_n, \theta_m)$, such that the total energy density, *E*, is given by the double summation over *N* frequencies and *M*(*n*) directions:

$$E = \sum_{n=1}^{N} \sum_{m=1}^{M(n)} S(f_n, \theta_{n,m}) \quad \text{(D.4.4-4)}$$

As can be seen from these equations, the essential difference between continuous and discrete spectra is that, for continuous spectra, energy is contributed by all frequencies and directions (for 2-D continuous spectra), whereas for discrete spectra, the wave energy contribution is non-zero only at particular frequencies (and at particular directions for 2-D discrete spectra). In the guidance below, discrete spectra are assumed to be used unless otherwise stated.

D.4.4.1.2 Measured Deepwater Wave Data

Ideally, long-term wave data measurement programs could replace the use of deepwater wave hindcasts and transformation modeling to shallow water. However, wave gages are expensive to install and maintain, and are often temporarily out of service for maintenance or repair. Nevertheless, wave measurements are extremely important for confirmation and verification of the results of hindcast modeling. For the Pacific Coast, the principal sources of wave measurements are the National Data Buoy Center (NDBC) and the Coastal Data Information Program (CDIP), which is supported by the State of California and the U.S. Army Corps of Engineers (USACE). There are also “records of opportunity” that may be obtained from oil company platforms, local agencies, and numerous engineering studies performed along the coast.

D.4.4.1.2.1 National Data Buoy Center

The NDBC (<http://www.ndbc.noaa.gov/>) is a branch of the National Oceanic and Atmospheric Administration (NOAA). NDBC has installed and maintained offshore meteorological and oceanographic buoys since the late 1960s. Many of these buoys have been in place at specific locations for a sufficiently long period such that reasonably accurate wave height statistics can be derived. (Federal Emergency Management Agency [FEMA] studies typically require a minimum of 30 years of data to achieve acceptable predictions.) Many other buoy locations are available with limited record periods and are not suitable for direct statistical prediction of extremes. However, the data from any wave sensor might still be very useful to check wave hindcast models.

Figure D.4.4-3 shows locations of the NDBC Met-Ocean buoys in the Southern California area; Figure D.4.4-4 shows locations in the North Pacific. Not all of the buoys that are shown on the maps are always present, and often those shown are temporarily removed for maintenance and may be replaced in slightly different locations. Data inventories (locations, dates of installation, and records) are available at the website noted above. Most wave data are in the form of 1-D spectra with summaries of wave height and periods (spectral peak and average); very few have wave directional information.

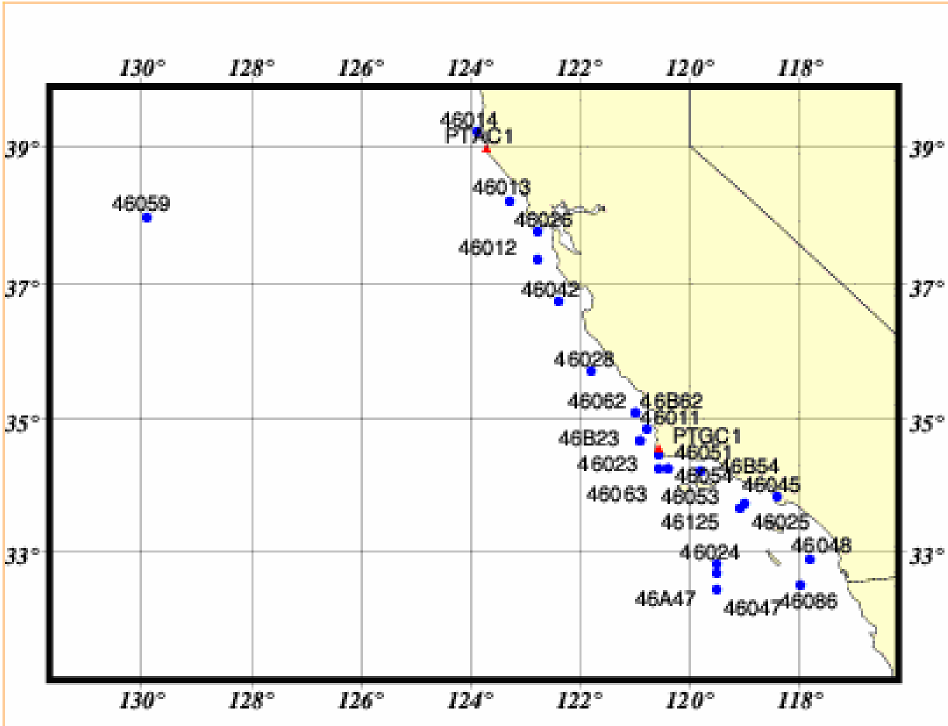

Figure D.4.4-3. NDBC Buoy Locations near Southern California

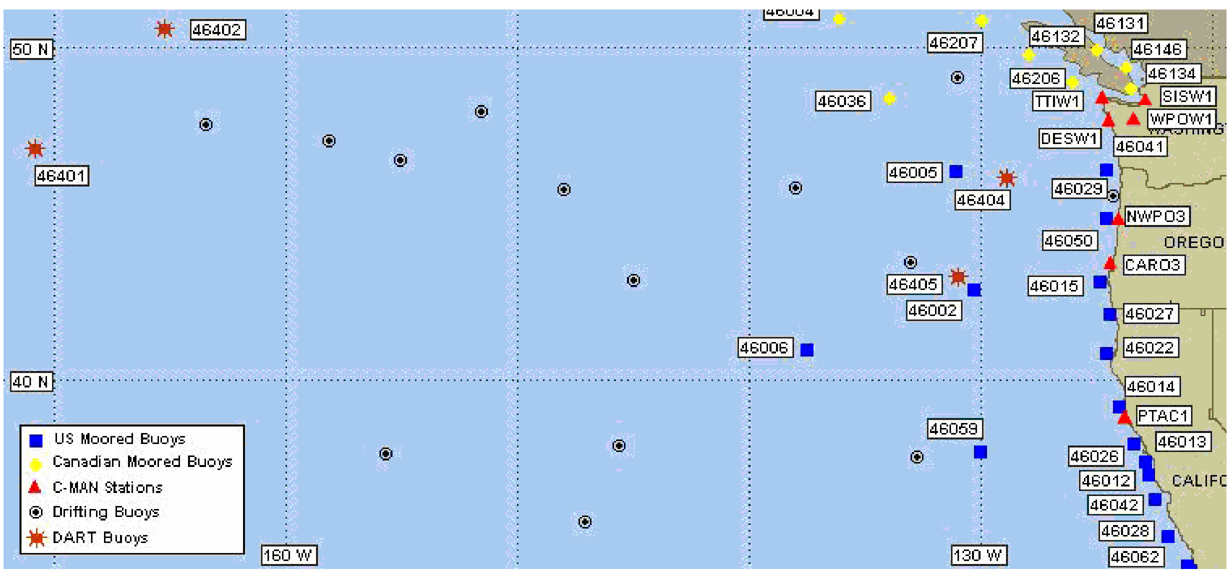

Figure D.4.4-4. NDBC Buoy Locations in the North Pacific

The NDBC buoys record wave amplitudes by sensing the vertical heave acceleration. To obtain wave direction estimates, the sensors include two horizontal accelerometers. The moorings are designed to minimize the restraints on the buoy motions, but it should be recognized that this is not a perfect decoupling; in particular, the response to longer waves (periods greater than 20 seconds) may be affected. In the most recent buoy configuration, wave data are recorded for 20 minutes each hour. For directional spectra buoys, the outputs from the horizontal accelerometer sensors are used to derive a mean wave direction and an angular spreading. The estimates of angular spreading are inherently poor, as only two coefficients can be determined to represent what should commonly be a narrow directional distributional function associated with swells.

D.4.4.1.2.2 Coastal Data Information Program

The CDIP employs 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, Office of Naval Research, the State of California, and others. The program has been expanded recently to include installations on the Atlantic Coast, the Great Lakes, Hawaii, and other areas of the Pacific Ocean (<http://cdip.ucsd.edu/dbase/web_stations/public_station_directory.shtml>). Some older data include measurements by pressure sensors rather than buoys.

Data from the CDIP buoys are analyzed to give wave heights and estimates of wave directions. The basic sensors are accelerometers that sense vertical acceleration and two orthogonal horizontal accelerations. These exhibit limitations similar to those discussed above for NDBC directional wave buoys. The “apparent” horizontal accelerations may be contaminated by the buoy responses in “tilting” (pitch and roll). The relative magnitudes of the two components provide a good approximation to mean wave direction at each frequency band within the spectrum, but directional spread estimates are inherently limited because only two components are available to define what might be a relatively narrow directional distribution in shallow waters.

D.4.4.1.3 Hindcast Wave Data

Hindcast wave data consist of estimates of wave parameters derived from weather data, rather than actual wave observations, through application of wave generation models. Some earlier flood studies used hindcast wave data developed by the Navy’s Fleet Numerical Weather Central, which was analyzed and published by Meteorology International Inc. (MII, 1977). The Wave Information Studies (WIS) developed by the USACE Waterways Experiment Station at Vicksburg have also been used. The WIS data include statistical summaries of wave conditions and time series for the period from 1956 to 1975 for the Pacific Coast (WIS Report 17 by Jensen et al., 1989), with a separate report (WIS Report 20 by Jensen et al., 1992) for Southern California. An important limitation of these older studies is that they did not include swells from the Southern hemisphere or from Northeast Pacific tropical storms. The WIS period also corresponded to a time when satellite meteorological measurements were not available or were very limited, and the number of data buoys was much smaller than it is now.

Significant improvements in the analysis of historical meteorology have been made in recent years. Wind fields have been re-analyzed and have been used with so-called third- and fourth-generation wave hindcast models to yield improvements in wave hindcasts over periods of 20-30 years. The advent of very economical high speed computing capabilities has enabled directional wave spectral modeling to be performed on the entire Pacific Ocean, and even globally. These newer models have been calibrated and verified by comparison with measured data at offshore buoys and with satellite scatterometer measurements.

Wave hindcast databases that can be considered for use in an FIS include:

- WAVEWATCH III by Fleet Numerical Meteorology and Oceanography Center (FNMOC);
- WIS by the USACE; and
- Global Reanalysis of Ocean Waves (GROW) by Ocean Weather Inc.

D.4.4.1.3.1 WAVEWATCH III

The U.S. Navy FNMOC prepares weather and wave forecasting for all oceans of the world (<https://www.fnmoc.navy.mil/PUBLIC/>). The basic model, known as WAVEWATCH III, computes directional wave spectra using 25 frequency and 24 direction bins. Products include sea wave heights, periods, and directions; swell wave heights, periods, and directions; and several other meteorological parameters. The emphasis of the available data is forecasting. There is an historical database dating back to July 1997 that can be downloaded (with permission) from the FNMOC site. This database is too short for estimating extreme waves. However, given that the model is readily available and can be downloaded from the WAVEWATCH site, the hindcasting model could conceivably be extended by a user as long as the analyzed wind fields for earlier years are prepared or available. WAVEWATCH III is a third-generation deepwater wave prediction model (WAMDIG, 1933; Komen et a1., 1994).

D.4.4.1.3.2 Wave Information System

The WIS was developed by the Waterways Experiment Station of the USACE (<ftp://wisftp.wes.army.mil/pub/outgoing/wisftp/>). WIS reports cover both the U.S. coasts and the Great Lakes. Wave hindcast data include separate values for sea and swell wave heights, periods, and directions. Many stations are located close to shore and include some portion of the shallow water transformations. For the Pacific Coast, the period of hindcasting is 1956 through 1975. Figures D.4.4-5 and D.4.4-6 illustrate examples of locations for which WIS data can be downloaded from the referenced website.

WIS is currently being updated to add coverage for a more recent time period. It has been suggested that WIS may overestimate wave heights along the Pacific Coast. Consequently, if WIS data are to be used in a study, the Mapping Partner must review them to assess their accuracy by comparison with other data available for the area.

D.4.4.1.3.3 Global Reanalysis of Ocean Waves

GROW data are available from Ocean Weather Inc. at <www.oceanweather.com/metocean/grow/index.html>. These data include the results of a hindcast modeling system that covers the entire Pacific Ocean. The data are continually updated after comparisons with buoy measurements and scatterometer satellite observations. The data include a total of 23 parameters including heights, periods and directions for seas and swells. Also included are wind speed and direction, directional spreading of wave energy, and spectral moments (first and second). The hindcasts are based on directional spectral modeling using 23 frequency bands by 24 direction

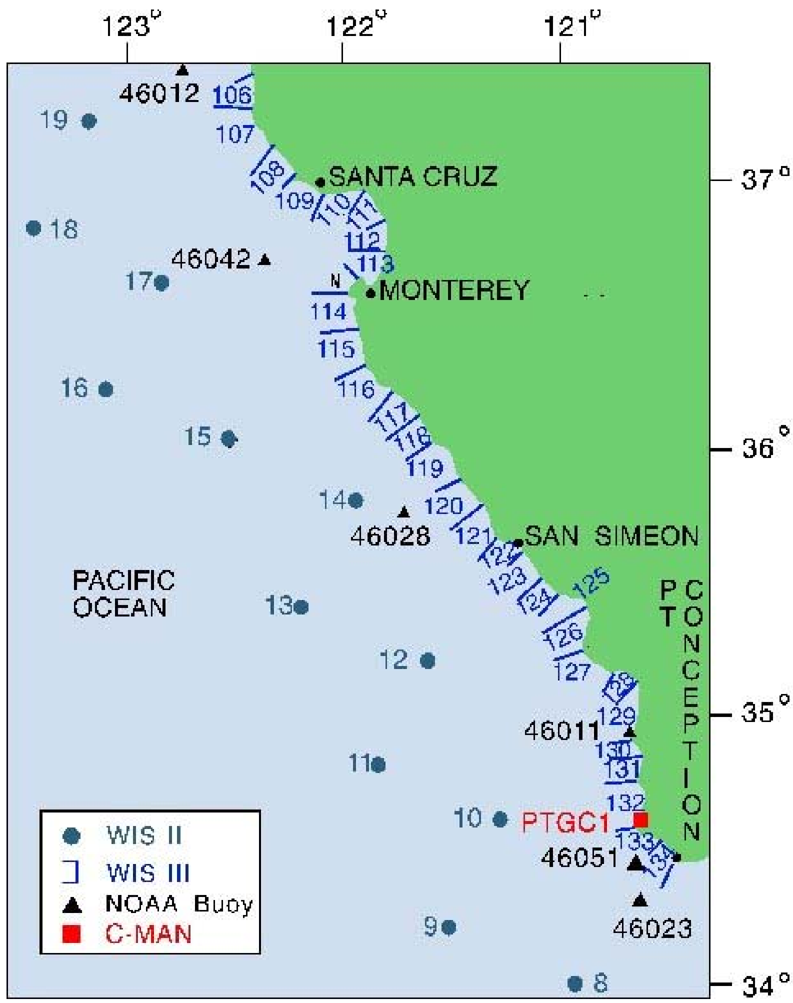

Figure D.4.4-5. WIS Stations in Central California

bands. GROW data are available at 3-hour intervals beginning January 1, 1970 through present, on grid points at every 0.625 degrees latitude and 1.25 degrees longitude. Figure D.4.4-7 shows some of the grid points that are available along the Pacific Coast.

The wave data files can be purchased in ASCII format. Standard output includes 23 parameters (19 meteorological and wave parameters) every 3 hours for the period of the hindcast (1970 to the present). The data include:

- Sea heights (energy), periods, and directions
- Swell heights (energy), periods, and directions
- Significant wave height, dominant period, and dominant direction (from sea or swell)
- Spectral moments (m_1 and m_2)
- Angular spreading parameter (related to the exponent n in $\cos^n(\theta - \theta_0)$).

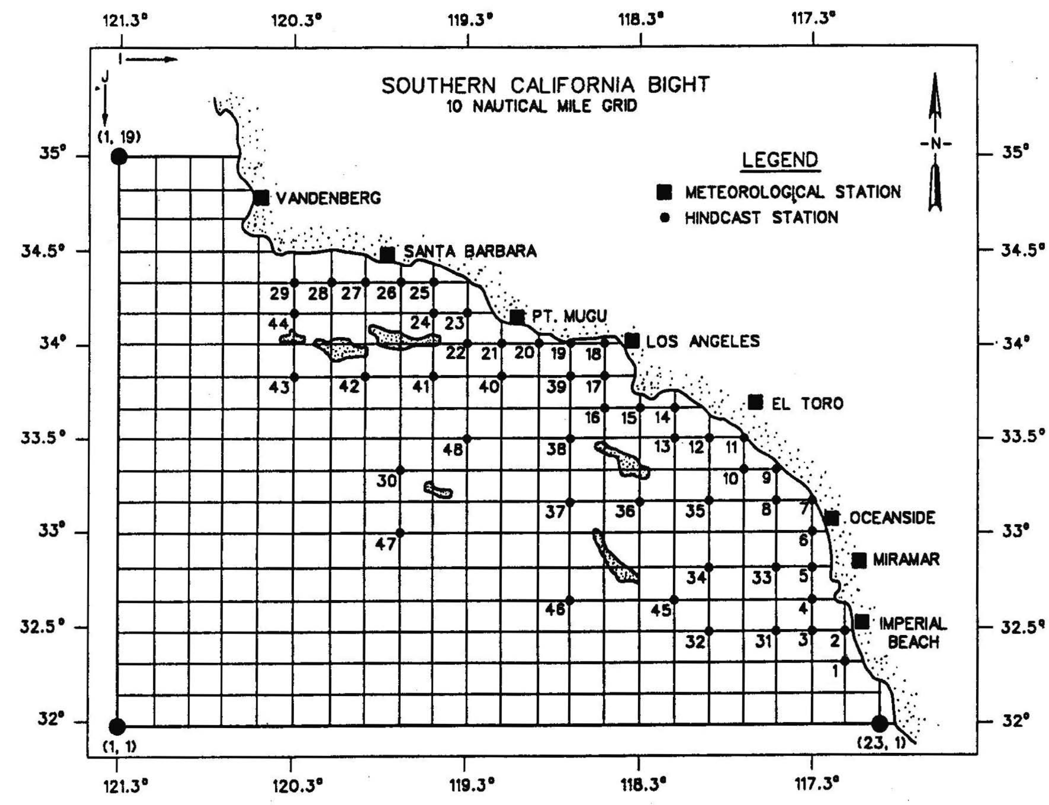

Figure D.4.4-6. WIS Stations in Southern California

From this data, directional spectral inputs for application to shallow water wave transformations can be specified. The directional spreading is available, but it is necessary to adopt a spectral peakedness factor in a Joint North Sea Wave Project (JONSWAP) type spectral formulation. The spectral form should be taken (after Goda, 1985) as:

$$S(f,\theta) = S(f)\,G(\theta) \qquad \text{(D.4.4-5)}$$

$$S(f) = \alpha H_s^2 T_p^{-4} f^{-5} \exp[-1.25(T_p f)^{-4}]\,\gamma^{\exp[-(Tpf-1)^2/2\sigma^2]} \qquad \text{(D.4.4-6)}$$

$$\alpha \cong \frac{0.0624}{0.230 + 0.0336\gamma - 0.185(1.9+\gamma)^{-1}}$$

$$\sigma = \sigma_a : f \le f_p$$
$$\sigma = \sigma_b : f \ge f_p$$

in which the directional spectrum is assumed to be separable into frequency and direction terms. Directional information is contained in the function G; subscript p denotes peak; α, γ, and σ are parameters with $\gamma = 1$ for sea and 9 for swell; $\sigma_a = 0.07$; and $\sigma_b = 0.09$.

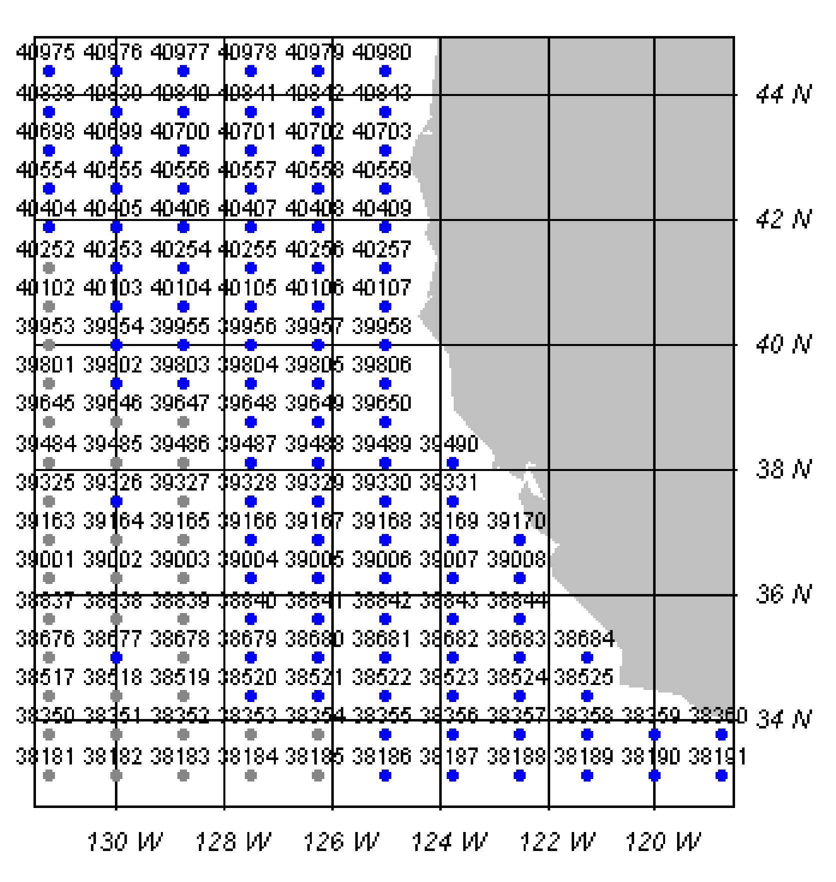

Figure D.4.4-7. Example of GROW Station Locations Along the Pacific Coast

Directional spreading is modeled using the following cosine power function:

$$G(\theta) = G_0 \cos^n (\theta - \theta_{main}) \qquad \text{(D.4.4-7)}$$

in which θ_{main} is the main wave direction (MWD) and n is the directional spreading index. The relationship between the angular spreading parameter in the GROW hindcast (ANGSPR) and n is as follows:

$$n = \frac{2 \times ANGSPR}{1 - ANGSPR} \qquad \text{(D.4.4-8)}$$

and

$$G_0 = \frac{1}{\pi} 2^{n-1} \frac{\Gamma^2 (n/2 + 1)}{\Gamma(n+1)} \qquad \text{(D.4.4-9)}$$

where Γ is the gamma function. Goda suggests that G_0 should be treated as a function of frequency relative to the peak frequency. This refinement may not be essential; sensitivity tests have shown that the practical difference in results after wave transformation routing to shallow water is negligible.

GROW assumes deepwater (depth > 3,200 feet) at the hindcast point. The reference GROW point should be taken offshore of this depth and clear of all headlands, islands, and shoals that may cause wave directions to be modified. Wherever possible, wave data should be evaluated by comparison with measurements that may be available in the study area.

D.4.4.1.3.4 Hindcast Wave Data Comparisons

In the future, alternative sources of wave data such as longer records of direct measurements from offshore buoys, improved wave modeling from WIS or WAVEWATCH III may be available and may be advantageous for use. The principal restriction of these alternative sources at present is that the WAVEWATCH III data cover a limited period, and the WIS data for the Pacific Coast are thought to give wave heights that are somewhat too large. It has also been noted that the wave periods reported by offshore buoys may be too low. Comparisons between data sources can be made where they overlap. Specifically, the GROW data overlap with the WIS data between 1970 and 1975, and with buoy data where available. There are generally no overlaps between the NOAA buoy data and the currently available WIS data ending in 1975.

Normally, GROW data are provided at 3-hour intervals, which should be adequate for any FIS. This yields 2,920 records per year (2,928 in a leap year). The GROW data include 23 parameters (19 meteorological and oceanographic parameters) at each time step, so a complete 30-year file would contain about 90,000 data lines. This may exceed the capacity of some common software, although many specialized packages are available for manipulation of data sets of this magnitude. The NOAA data are stored in annual blocks on the NOAA website. The WIS data are stored at 3-hour time steps with 15 parameters that include the separation of sea and swell. WIS II (Pacific Coast) provides a record from 1956 through 1975 in text format, in addition to statistical summaries.

At the present time, the GROW hindcasts may provide the most comprehensive and current data set for FIS use in most open coast locations.

D.4.4.1.4 Wave Transformations

D.4.4.1.4.1 Overview

The primary wave data used in a Pacific Coast FIS are obtained from offshore deepwater hindcasts and observations as described above. However, the deepwater wave characteristics cannot be used directly to describe flood processes onshore. During propagation from deep water to the shallow water at the study site, the waves undergo major transformations in amplitude and direction, which depend upon the bathymetry over which they travel. To determine the ultimate onshore wave effects and flood levels (erosion, runup, setup, overtopping, and so forth) the Mapping Partner must account for these changes in the wave characteristics by determining the *wave transformations*, for a particular study area and coastal setting.

The major transformation processes are refraction, diffraction, and shoaling, all of which alter the waves' heights, while refraction and diffraction also affect their paths. For more information on these fundamental wave processes, the Mapping Partner should consult either the Shore Protection Manual (USACE, 1984) or the Coastal Engineering Manual (CEM) (USACE, 2003). Other processes that may be important include local wave growth because of winds, wave-wave interactions, wave-current interactions, and reflection. The Mapping Partner shall consider and document these processes when appropriate.

The level of complexity of the Mapping Partner's wave transformation effort depends upon two major considerations. First is the complexity of the bathymetry in the site vicinity. If the site lies in an area that can be adequately characterized by straight and parallel depth contours, relatively simple wave transformation procedures may be entirely acceptable. If, however, the site is fronted by rapidly varying bathymetry, such as a steep, narrow canyon, or by islands or shoals, then the wave propagation behavior is correspondingly complex, and complex procedures are required.

The second consideration is the manner in which the transformed wave parameters will be used in subsequent surf zone and shoreline computations. Section D.4.5 includes three potential methods for wave setup computations that may be used depending on complexity of the surf zone, setting, and overall study methodology. These are: 1) a parameterized version of the Direct Integration Method (DIM); 2) a DIM numerical model; and 3) Boussinesq modeling. The parameterized DIM approach requires only the deepwater equivalent significant wave height, peak period, and peak enhancement parameter. The numerical DIM approach requires an equivalent deepwater wave frequency spectrum, and the Boussinesq approach requires a full directional spectrum or wave time series. The selection of transformation methods must therefore consider the input required in this subsequent analysis step.

The complexity of the analysis depends on the complexity of the site characteristics and dominant transformation processes that must be represented. In some study areas, both the shoaling zone and surf zone bathymetry may be relatively simple, and the offshore waves relatively uniform. In this case, complex transformation methods may not be required. For the case of simple bathymetry with straight and parallel contours, this may be accomplished with shoaling and Snell's Law for refraction. This approach may be applied to a single wave or to a wave spectrum. For more complex bathymetries and to account for other transformation processes (e.g., diffraction), transformation determinations based on 2-D hydrodynamic modeling, such as Boussinesq models, are needed. These models may be used to develop spectral transformations, or if the wave transformations are nonlinear, to transform the times series of the wave surface elevations. In sheltered waters or other areas where significant wave generation occurs in the shoaling zone, a 2-D spectral wave model that also accounts for wave generation may be desirable. The guidance below provides background primarily on the spectral transformation methods.

As shown in the accompanying flow chart (Figure D.4.4-8), the determination of wave transformations for a typical Pacific Coast FIS includes four major steps:

1. Review site conditions and available wave information.
2. Develop a transformation approach.
3. Perform the transformation from deepwater to nearshore.
4. Convert nearshore results to equivalent deepwater conditions.

If the study site lies in an area of extremely complex bathymetry, a high resolution transformation model might be required to resolve local refraction and diffraction behavior. Rather than perform the entire analysis using a highly detailed model in offshore areas where conditions do not require it, the Mapping Partner can establish the wave transformations using a two-step process, first bringing the waves close to shore with a model of normal resolution, and then performing a second nearshore transformation of those waves using a fine grid in the more local area of complex bathymetry.

The spectral method of wave transformation relates shallow water spectra with offshore spectra through multiplication by an array of wave transformation coefficients. The transformation array is developed by application of a 2-D hydrodynamic wave transformation model applied over the bathymetry between the site and the deepwater data source points. It is recognized that there may be situations where alternative methods may be more appropriate. For example, wave transformations in sheltered waters may be better determined using a spectral wave model that also considers wind wave generation (see Subsection D.4.4.1.5).

The Mapping Partner must perform a thorough and detailed review of site conditions as part of this wave transformation analysis. A comprehensive summary of the site should include the following items:

- Bathymetry sets for the offshore and nearshore regions.
- Locations for several cross-shore transects in the nearshore region that encapsulate the local character of the coastline and the seabed steepness.
- Locations and types of coastal structures.
- Identification of special processes (such as diffraction, reflection, or the presence of strong currents or local winds) that might influence wave transformation.
- A specific definition of the site boundary for the analysis.
- The location of the source offshore spectral wave data.
- Appropriate tide level. In most cases a single tide level on the order of mean higher high water (MHHW) is sufficient for flood studies. However, higher water levels or a range of levels may be considered as appropriate.

The Mapping Partner shall select nearshore points that act as output locations for the transformation of the offshore wave spectra. It is recommended that the Mapping Partner shall select nearshore points just outside the surf zone as defined by the large waves breaking during extreme events. Engineering judgment shall be used to determine transect spacing. It is recommended that transects extend far enough in the seaward direction, so the most seaward point is outside of the surf zone. An example approach to selecting a nearshore point and a series of cross-shore transects is shown in Figure D.4.4-9. The shore transects are located to represent reaches of shoreline with similar wave exposure and beach characteristics including man-made features such as coastal structures.

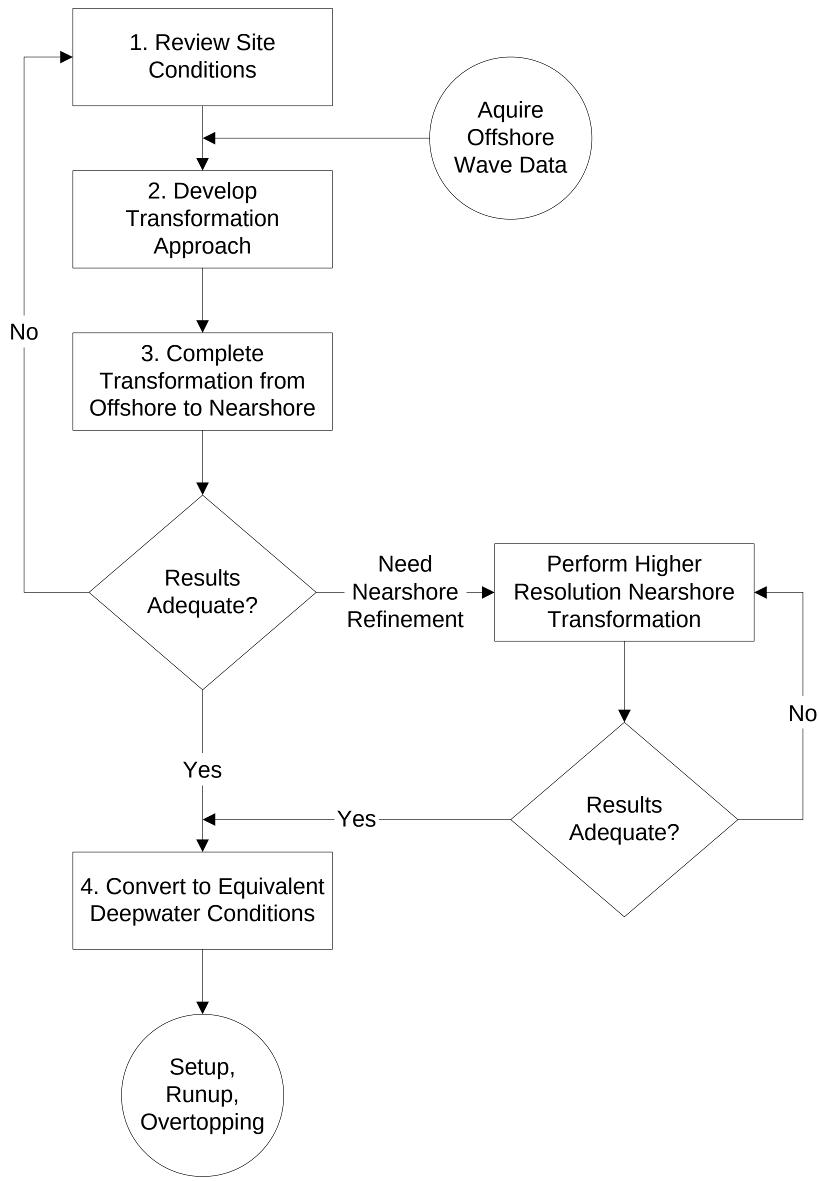

Figure D.4.4-8. Flow Chart for Wave Transformation Analysis

As a necessary part of quality control, the Mapping Partner is responsible for ensuring that numerical transformation results adequately represent site behavior. If numerical methods that have not been validated are used, the Mapping Partner shall consider the need to obtain field data measurements to validate the wave transformation procedures.

D.4.4.1.4.2 Spectral Transformation Methods

In the spectral method, the offshore wave spectrum is converted to a nearshore wave spectrum using an array (or arrays) of wave transformation coefficients for discrete wave frequency and offshore direction intervals. A conceptual diagram of the spectral method using an array of transformation coefficients is shown in Figure D.4.4-10.

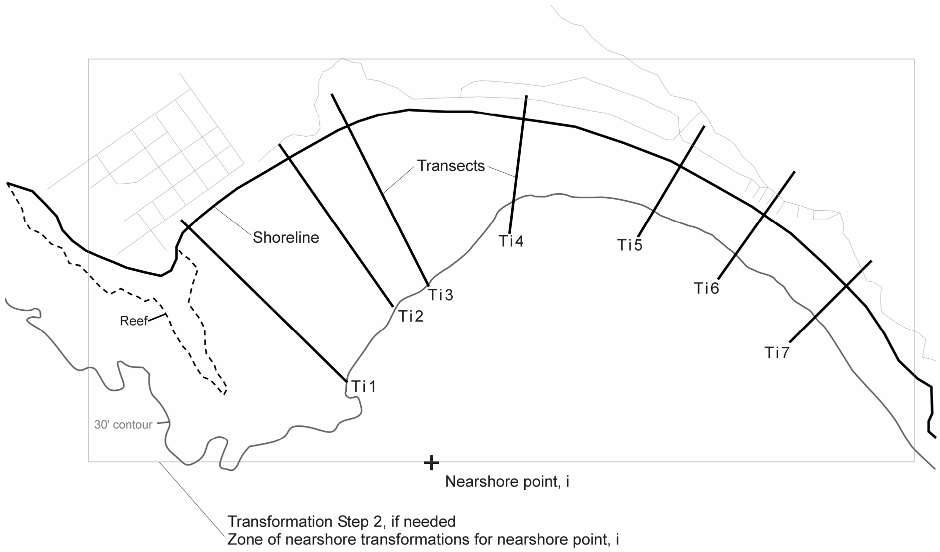

Figure D.4.4-9. Example Placement of Nearshore Point and Location of Cross-Shore Transects

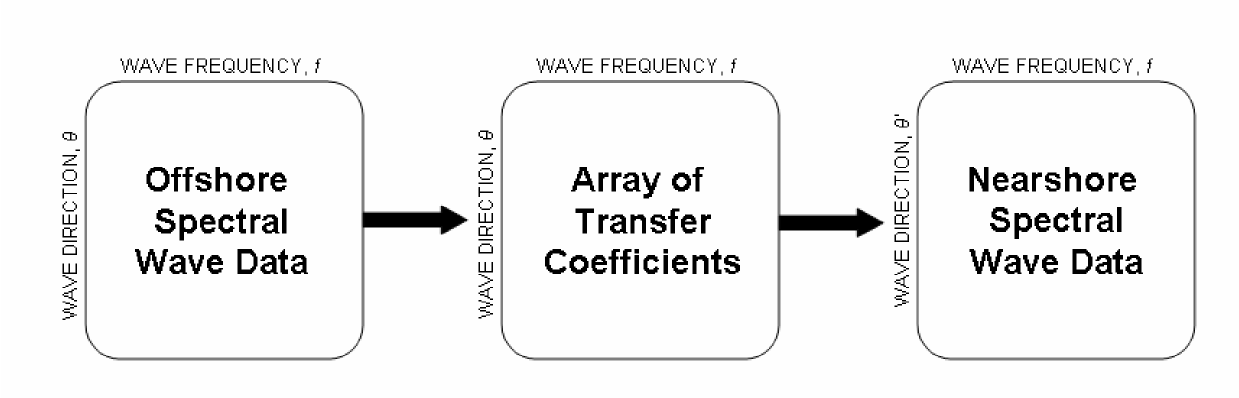

Figure D.4.4-10. Conceptual Diagram of Spectral Transformation

This transformation process should incorporate all important transformation processes in the study area, including shoaling, refraction, sheltering, diffraction, island blocking, and so forth. In this process, the discrete frequencies remain the same as they were in deepwater; however, the discrete directions change owing to wave refraction. At the nearshore location, the spectrum is consolidated to a single direction per frequency, and stored for later use. This consolidated spectrum is also transformed back to deepwater for a different set of applications. The back-transformation allows the Mapping Partner to work with equivalent deepwater conditions; the back-transformed deepwater spectrum is characterized by one direction per frequency.

Spectral transformations are often based on application of a 2-D hydrodynamic model to develop the array of transformation coefficients, and this level of analysis will be appropriate in most situations on the Pacific Coast.

Transformation of the Deepwater Spectrum to a Nearshore Location

The array of transformation coefficients can take several forms depending on the methods used to calculate them; more complex site conditions require more complex calculations to achieve adequate accuracy. A representative conceptual form of the transformation relationship is:

$$S_{ns}(f_n,\theta_{n,m}^{'}) = S_o(f_n,\theta_{o,n,m})K_s^2(f_n)\{K_r^2(f_n,\theta_{o,n,m})G_\theta(f_n,\theta_{o,n,m})\} \qquad \text{(D.4.4-10)}$$

in which subscripts *o* and *ns* denote offshore and nearshore conditions, and *m* and *n* denote the discrete direction and frequency components, respectively; the prime denotes the transformed nearshore direction. K_s is the shoaling coefficient, K_r is the refraction coefficient, and $G_\theta\left(f_n,\theta_{o,n,m}\right)$ accounts for the change of direction between offshore and nearshore (not modifying the energy level of the spectral element); taken together, K_r and *G* represent the effects of refraction.

In studies where the DIM approach will be used for setup and runup, calculation of the full nearshore directional spectrum is unnecessary because the subsequent setup and runup calculations require only the frequency spectrum (no direction information is required after the wave transformation calculations). Then the spectral transformation becomes:

$$S_{ns}(f_n) = K_s^2(f_n)\sum_{m=1}^{M(n)} K_r^2(f_n,\theta_{o,n,m})S_o(f_n,\theta_{o,n,m}) \qquad \text{(D.4.4-11)}$$

where $M(n)$ is the number of direction components for the n^{th} frequency component.

If the nearshore directional spectrum is desired, the direction transformations must be determined. For straight and parallel depth contours, Snell’s Law gives a simple relationship based on offshore angle of wave approach, nearshore depth, and wave frequency. Otherwise, the directional transformation can be complex owing to converging and diverging zones of wave energy; the Mapping Partner shall develop the directional transformation with care. One approach is to develop smoothed directional distributions at the shallow water location for each frequency. This approach lends itself to the application of discrete back-refraction models and is used by CDIP. An alternative method is to establish an array of mean wave directions at the shallow water location based on transformation of directional distributions from each offshore direction and selected frequency; this approach lends itself to application of contemporary 2-D spectral wave transformation models.

In areas where the bottom contours are reasonably straight and parallel, the Mapping Partner may choose instead to carry out the transformation using simplified methods for straight and parallel contours. In this case, the necessary linear wave transformation coefficients are given by:

$$K_r^{\ 2} = \cos\theta_o / \cos\theta \qquad \text{(D.4.4-12)}$$

$$K_s^{\ 2} = C_{Go} / C_G \qquad \text{(D.4.4-13)}$$

where C_G is the group velocity and the subscript o denotes the deepwater location; the unsubscripted variables are at the nearshore site. The refracted wave directions are given by

$$\sin\theta = \frac{C}{C_o}\sin\theta_o \tag{D.4.4-14}$$

and

$$C_G = \frac{C}{2}\left[1 + \frac{2kh}{\sinh 2kh}\right] \tag{D.4.4-15}$$

The wave celerity, or phase velocity, is given by $C = L/T$ where T is the wave period and L is the wave length, related by the implicit dispersion equation:

$$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi h}{L}\right) \tag{D.4.4-16}$$

The water depth is denoted by h and the gravitational acceleration by g.

Consolidation of the Nearshore Spectrum

After the nearshore spectrum $S_{ns}(f_n, \theta'_{n,m})$ is established, it is consolidated into a discrete spectrum with a single direction for each frequency. The requirements for the consolidated nearshore spectrum are: (1) that total energy be preserved, and (2) that the longshore component of momentum be preserved.

The total energy of the nearshore spectrum for each frequency, f_n:

$$S_{ns}(f_n) = \sum_{m=1}^{M} S_{ns}(f_n, \theta'_{n,m}) \tag{D.4.4-17}$$

The effective direction, $\theta'_{eff,n}$, for each frequency is determined from

$$\theta'_{eff,n} = \frac{1}{2}\sin^{-1}\left(\frac{1}{S_{ns}(f_n)}\sum_{m=1}^{M} S_{ns}(f_n, \theta'_m)\frac{C_G}{C}\sin 2\theta'_m\right) \tag{D.4.4-18}$$

in which C_G and C are the group and phase velocities, respectively.

Transformation of the Consolidated Nearshore Spectrum to Deepwater Equivalent

After the equivalent nearshore spectrum has been determined, it can be back-transformed to deepwater by applying the shoaling or refraction coefficients previously found. The equivalent deepwater spectrum is the nearshore spectrum de-shoaled to deepwater, but retaining the influence of refraction. Therefore, the equivalent deepwater spectrum is the spectral version of the equivalent deepwater wave height, $H_0{}'$; traditionally used for coastal analyses. The equivalent deepwater spectrum, $S_o^{'}(f_n)$; can be calculated from either the nearshore spectrum or the incident deepwater spectrum. In the first case, the nearshore spectral elements are divided by the appropriate shoaling coefficients:

$$S_o^{'}(f_n) = \frac{S_{ns}(f_n)}{K_s^2(f_n)} \tag{D.4.4-19}$$

In the second case, the deepwater equivalent spectrum is calculated directly from the incident deepwater spectrum by incorporating the effect of refraction:

$$S_o^{'}(f_n) = \sum_{m=1}^{M(n)} K_r^2(f_n, \theta_{o,n,m}) S_o(f_n, \theta_{o,n,m}) \tag{D.4.4-20}$$

Spectral Transformation Output

Output from the spectral transformation approach should consist of the following items:

- A wave frequency spectrum outside the breaker line at one or more nearshore point(s);
- An equivalent deepwater wave spectrum;
- An equivalent deepwater significant wave and a peak period;
- Three spectral moments (m_0, m_1, and m_2) for the equivalent deepwater wave spectrum; and
- Directional information, if required, for the equivalent offshore spectrum.

Wave spectra for each transect in the nearshore are converted to deepwater conditions and equivalent deepwater wave parameters are calculated from the spectra. The necessary spectral moments can be calculated from the following equation:

$$m_i = \sum_{a \le f_n \le b} f_n^{\,i} S(f_n) \tag{D.4.4-21}$$

where m_i is the i^{th} spectral moment and (a,b) are suitable cutoff frequencies. The spectral moments are used to calculate the spectral width (or narrowness of the peak of the frequency spectrum), which is important for the setup calculations discussed in Section D.4.5. The spectral moments should be calculated by summing the spectral terms from the low frequency cutoff, a, to the high frequency cutoff, b. The low frequency cutoff is typically assumed to be 0.0 Hz, but it is often as high as 0.03 Hz, depending on the analysis methods employed to generate the offshore spectrum. For the purposes of calculating the spectral width only, the high frequency cutoff should be limited to about 1.8 f_p, where f_p is the peak frequency (Goda, 1983). This cutoff is recommended so that the higher frequency wind waves do not dilute the calculated “peakedness” of the spectrum.

4.4.1.4.3 Regional Transformation and CDIP

Accurate prediction of waves in the nearshore region requires modeling the evolution of the deepwater wave spectrum across the continental shelf. In some regions such as Southern

California, offshore islands must also be taken into account. As a result, predicting waves at a single nearshore location generally requires setting up a relative large bathymetry grid, or a series of nested grids, to adequately address the sheltering and shallow water transformation of the incident waves.

Given the relatively large time and computational investment required to set up such a model for a single coastal site or short reach of coast, government agencies (NOAA, USACE, U.S. Geological Survey [USGS], U.S. Navy) are frequently adopting a broad regional wave modeling approach. There are several commercial and public domain spectral wave models that can be used for regional shallow water wave problems, and relatively large-scale regional wave modeling has become computationally and economically tractable with present computer technology. Wave model domains are prepared to provide predictions for relatively long sections of coastline (e.g., the entire Southern California Bight), and sheltering and shallow water effects are pre-computed to the extent permitted by the model resolution. Where such data are already available, Mapping Partners should adopt them if possible, and focus study resources more efficiently on specific localized environment factors (e.g., an ebb shoal at an inlet, or nearby reflective coastal structures) that may influence flood levels. As noted before, a second high-resolution nearshore transformation step may be needed.

Should a Mapping Partner be required to undertake development of a regional numerical transformation model, significant considerations include not only which of the available spectral wave models should be used, but especially the choice and implementation of the model's various tools and variables (such as grid characteristics, boundary conditions, and parameterized wave physics) to achieve sufficiently accurate results. Perhaps the most important of these model factors is whether any nonlinear aspects of the wave spectrum evolution from the shelf break to a location outside the surf zone need to be included. In most cases, these nonlinear effects can be neglected, and the Mapping Partner can use a fully linear approach in which the regional modeling only has to be performed once. Linear wave transformation coefficients are produced by the model in this instance, and can be used repeatedly to transform any deepwater wave spectrum to the coastline.

An independent regional transformation modeling effort is only undertaken by the Mapping Partner with concurrence of the FEMA study representative. In many instances, the Mapping Partner will adopt transformation data developed by others, such as the CDIP program described in the subsections below.

CDIP Coastal Wave Transformation Database

The CDIP at Scripps Institution of Oceanography has implemented a spectral refraction modeling method to derive regional coastline wave predictions just seaward of the surfzone (O'Reilly and Guza, 1991). The model accounts for island blocking, wave refraction, and wave shoaling. Spectral refraction back-refracts wave rays from the site of interest to unsheltered deepwater over the entire range of possible wave frequencies and wave directions. The retained starting and ending ray angles are then used to map a deepwater directional spectrum to a sheltered or shallow water spectrum at the back-refraction site. The resulting solutions are more realistic than those obtained using an assumption of unidirectional monochromatic deepwater waves. The Mapping Partner should consult technical documents from CDIP (2004a and 2004b) for a complete description of model validation and user's documentation.

When available, the Mapping Partner shall adopt CDIP transformation data to carry out the deepwater to nearshore wave transformation. An overview of the general steps to be followed by the Mapping Partner in cooperation and coordination with CDIP for the development of nearshore wave information is shown in Figure D.4.4-11. The primary steps to be taken include:

1. Ensure that local bathymetry data are accurate and up-to-date; if needed, update the bathymetric grid and the CDIP transformation coefficient database for the study area.

2. Validate coefficients with local wave data if available, and assess the need for additional validation measurements.

3. Transform selected deepwater (unsheltered) wave hindcast spectra to the nearshore model sites using the reviewed transformation coefficients.

These steps are discussed below.

Local Bathymetry Assessment

CDIP maintains regional wave model bathymetric grids, and software to create and modify them, for the coast of California. The water depths in the grids extend from approximately 15-foot depth out to the continental shelf break. The grids are derived primarily from digital hydrographic survey data collected by the National Ocean Survey (NOS) and distributed by the National Geophysical Data Center (NGDC). The coastal coverage of the NOS is particularly dense in Southern California and generally adequate for the remaining portions of the West Coast with either sizable population or frequently navigated coastal waters.

Each regional grid is produced from a very large number of NOS survey points. The data are screened for outliers and the resulting grids are plotted and visually inspected for errors.

Nevertheless, the local bathymetry at a study area remains a potential source of modeling error. Bathymetric errors may be the result of old or sparse surveys that fail to resolve a shallow water feature, or from changes in the local bathymetry owing to nearshore processes or dredging. As an initial task in the wave hindcast process, the Mapping Partner shall obtain and review local bathymetric information. This may include review of available survey maps for the area, a datasearch for bathymetric surveys performed by agencies other than NOS, and discussions with local authorities and local mariners. The Mapping Partner should then meet with CDIP and FEMA representatives to review this information and assess whether changes to the existing regional model grid and the model transformation coefficient database are needed. In addition, the need for new field measurements for model validation should be determined at this time.

Transformation Coefficient Validation

CDIP has validated the spectral refraction wave model predictions at numerous locations throughout Southern California over the past 15 years. This has provided some assurance that

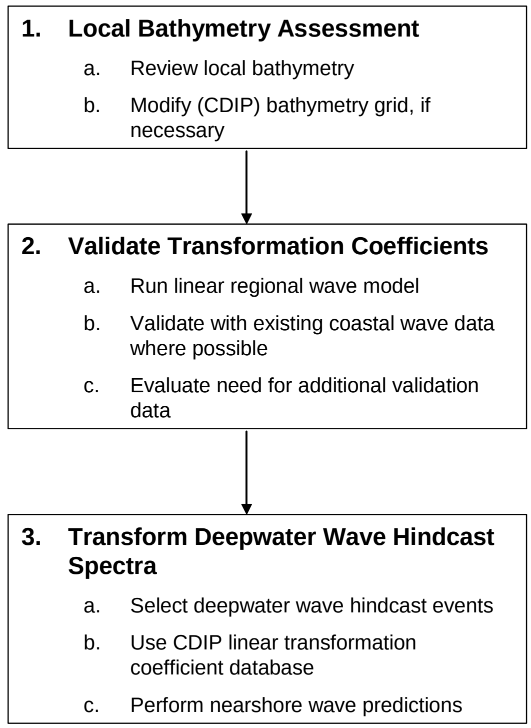

Figure D.4.4-11. Flow Chart of Tasks to Derive Nearshore Wave Hindcast Information for a FEMA Study Area

refraction and shoaling are the dominant transformation processes on narrow continental shelves such as those found on the West Coast. The various validation studies have also shown that significant model prediction errors can occur owing to model boundary condition errors (errors in the deepwater directional wave spectra and/or local bathymetry) or a neglected physical process such as wave reflection from a cliff-lined coastline.

Therefore, the second task in developing wave hindcasts for a FEMA study area is to assess the need for additional wave model validation. Mapping Partners will meet with FEMA and CDIP representatives to discuss the local geographic setting and determine if there are specific bathymetric or topographic features that might require modeling of additional physical processes. CDIP can also provide information on existing wave measurements in or near the study region that could be used for validation purposes.

The collection of wave measurements for model validation is an expensive and time-consuming task because both deepwater directional data and nearshore wave data are required, and data must be collected for a long enough period of time to observe a variety of wave events. The decision on whether to attempt additional model validation should be based in part on overall FEMA regional wave model information needs, and must be approved by the FEMA study representative.

The final task is to transform deepwater wave hindcast spectra to the nearshore using the reviewed, and possibly updated, spectral transformation coefficients from the CDIP database.

D.4.4.1.4.4 Local Seas

Local winds can affect waves during propagation; the regional transformation method described above does not include consideration of the effects of local winds. If local seas are considered important to the events being modeled, it is recommended that they be superimposed as a separate wave train, and integrated into the nearshore spectra. This can be accomplished by taking the estimated directional sea state, in spectral form, and applying the transformation coefficient array, as if it were generated offshore at the same or similar directions. If islands or shoals offshore of the wind field affect the transformation coefficients such that the site is artificially sheltered, an additional transformation is needed to refract the seas to the site.

D.4.4.1.4.5 High-resolution Nearshore Transformation

Once the primary transformation of waves to the nearshore point(s) is complete, it may be necessary to perform a secondary transformation to account for the effects of local complex bathymetry. For this, the Mapping Partner may use a spectral wave model with the ability to propagate the wave components from the nearshore point(s) to the local transects.

A number of such models are in wide use; the Mapping Partner should review FEMA's list of approved models for candidates. Should a model that is not on the approved list be deemed advantageous for the study, the Mapping Partner should coordinate with the FEMA study representative.

Specific model user's manuals and documentation must be relied upon for guidance in modeling considerations. In any case, model grids should be constructed with appropriate resolution to simulate irregular bottom contours and any special bathymetric features. The grids should also be constructed, so the transect locations are not close to the grid boundaries. The Mapping Partner shall locate output points on the model grids corresponding to the locations of the local transects. A sufficient number of modeling runs shall be performed so that a 2-dimensional (frequency and direction) energy transfer coefficient array can be constructed for each local transect. These coefficients are similar to those developed for the primary deepwater to nearshore transformation. Once the transfer coefficients have been determined, the Mapping Partner shall convert the wave spectra at the nearshore point(s) to wave spectra at the location of each transect using methods discussed earlier.

D.4.4.1.5 Waves in Sheltered Waters

D.4.4.1.5.1 Storm Wind Fields

The ocean wave data discussed above may not be available for sheltered waters. In this case, local wave generation modeling may need to be undertaken. A first step in this effort is the acquisition of necessary wind data. In sheltered waters, transitions between land topography and open water areas affect the characteristics of the wind field. The wind *fetch* is the open water area over which wind waves are generated, and storm seas in sheltered waters are limited by the size and shape of the water body ("fetch-limited" seas). Wind speed, wind duration, fetch length, and water depth are the main parameters that determine the heights and periods of locally generated wind waves. (See USACE, 2003 and 1984 for details.)

Time series of 2-D (surface) wind fields are the most realistic representations of storm conditions. Several numerical wave models have the capability to incorporate 2-D time-varying wind fields, but adequate wind field data are not typically available. Instead, point wind data are most commonly measured by anemometers or wind gages operated by government agencies or airports. To use such point data, the Mapping Partner may follow a procedure in which:

- Extreme wind speeds are estimated from wind gage measurements at a point (extremal analysis is discussed in Section D.4.3);
- The wind speed duration is adjusted to optimize for the fetch-limited wave condition; and
- The fetch-limited wind condition is applied as a steady-state boundary forcing function in a 2-D numerical model.

A wind gage might not be located at the study site, but several gages may be located within the vicinity of the site. The selection of wind data from a particular gage should be based on data availability, proximity of the gage to the site, the length of the data record, and the type of data recorded. The goal is to obtain the longest record of quality data that is representative of wind conditions at the study site.

Anemometer measurements of wind data are recorded in various ways. Average wind speed and direction over a given interval (i.e., 2 minutes or 1 second) are typically recorded at regular intervals (i.e., every hour). Peak gust wind speed and direction of the “fastest mile” wind speed may also be reported. Wind roses that show the percent occurrence of wind speeds for compass directions may also be available, and are useful for understanding wind conditions but may not be suitable for estimating extreme wind conditions associated with the 1% annual chance flood.

Various adjustments to wind data recorded by wind gages may be necessary. The USACE CEM (2003) and *SPM* (1984) contain detailed procedures for adjusting wind data. It may be necessary to adjust wind data for the following:

- *Level*, if the wind speed is observed at a level other than the standard anemometer height of 10 meters;
- *Duration*, to obtain the appropriate fetch-limited wind speed for wave hindcasts corresponding to the averaging interval;
- *Overwater*, if winds measured over land are used to hindcast waves over water; and
- *Stability* of the atmospheric boundary layer for fetches longer than 16 km.

See the CEM (USACE, 2003) or the SPM (USACE, 1984) for a detailed discussion of these adjustments.

The statistical methods described in Section D.4.3 should be used to estimate extreme wind speeds associated with the 1% annual chance flood. The Mapping Partner shall consider wind direction when estimating extreme wind speeds to include only winds that generate waves affecting the site. That is, the wind data should first be segregated into directional sectors corresponding to distinct meteorological events (i.e., storms occurring during different seasons that arrive from different directions).

Storm duration is also an important parameter for the characterization of the 1% annual chance flood and for use in estimating event-based-erosion (Subsection D.4.6.1). As discussed in Subsection D.4.2.4, the preferred approach is to consider storm episodes as they have occurred in nature, so duration is effectively bundled with intensity and direction information. If this cannot be done owing to lack of data, duration may be estimated by analyzing the persistence of high winds above a threshold.

D.4.4.1.5.2 Wave Generation Modeling in Sheltered Waters

Two-Dimensional Models

Subject to FEMA approval, spectral wave models can be used to calculate 2-D wind-wave generation. Such models are based on an energy balance equation that accounts for wave propagation processes and processes that add or remove energy from individual frequency and direction bands. The wind input to the models can be steady and uniform, spatially variable, or non-steady. The model depth grid shall encompass the entire fetch area of interest. Wind setup (surge) within the basin can be calculated by linking the models to 1- or 2-D surge models; the depth change caused by wind setup can significantly affect wind-wave generation in shallow waters.

Two-dimensional wind-wave generation models can be found on the FEMA-approved models list. A Mapping Partner shall review 2-D models available at the time of the study. Although steady-state modeling (time-constant wind, wave, and water level conditions) with a uniform wind field is common and is adequate for most flood studies, 2-D models may allow consideration of a spatially variable wind speed, possibly resulting in more accurate results. Similarly, a time-dependent approach can be considered if the time-variation of the winds is known, or if tidal excursions are important to either the wind-wave generation process itself, or to depth dependent wave transformations occurring in the generation area. Application of models in a time-dependant mode entails additional effort to determine appropriate parameters and to document the more complex calculations, but may provide more accurate results. Specific guidance for use of any model shall be obtained from the corresponding user's manual; model results shall be verified against observed data, whenever possible, to confirm validity of the model implementation.

Two-dimensional wave model output shall include nearshore frequency and direction spectra at specific locations, as well as wave height, period, and depth for model grid points. Wave spectral output shall be determined at a nearshore point and/or several transect points; the output directional and frequency spectra for most spectral models can be selected for specific grid points. Some models provide parameterized spectra rather than 2-D spectra. In such a case, the parameterized spectra can be converted to complete spectra by fitting a JONSWAP spectrum to the parameters as explained in the CEM (2003).

Parametric Methods

In some situations, such as when studying a small embayment, simplified parametric methods are appropriate. When using parametric methods, the Mapping Partner shall consult the latest version of the CEM (2003) for specific guidance. Depending on the site conditions and other study factors, straight-line, composite, or representative fetch methods may be used (CEM, 2003; PWA, 2004).

Selection of Wind Input

In sheltered waters, the small area of the water body often results in the hindcast waves being fetch limited. For these conditions, the averaging time used for the wind speed determination may have to be adjusted to correspond to the fetch-limited duration. For example, if the minimum wind duration corresponding to the fetch conditions is 30 minutes and the wind speed data are given as 10-minute averages, then the 10-minute averaged wind speed should be adjusted to a 30-minute averaged wind speed for use in the wave generation model; this adjustment may be done using methods described in the CEM. The computation is iterative because the minimum duration depends on the wind speed.

Such an adjustment is recommended when waves are determined by parametric methods. If 2-D numerical methods are used, then the appropriate user's manual for the numerical model should be consulted for specific guidance; an adjustment may not be needed in all cases.

D.4.4.1.6 Data Requirements

The Mapping Partner shall carefully choose the source and the location of the reference hindcast/observation point for the basic input wave data. This must be near the study site but far enough removed, so there is no interference from offshore islands and shoals. It is recommended that GROW data be given primary consideration, but alternative sources such as WIS data and measurements should always be considered and compared. Additional sources of offshore wave hindcast data continue to become available. The Mapping Partner should attempt to identify such newer data, which, if available, shall be approved by the FEMA study representative before use in a study.

D.4.4.1.7 Documentation

Documentation shall include details of the sources of wave and wind data. It should also include comparisons between alternate sources (where several may be available) and with any local measurements. Documentation of the incident deepwater waves used for routing to shallow water should include periods, directions, and directional spreading. The selection of coefficients for angular spreading and spectral peakedness parameters shall be clearly stated and justified.

Methods of extrapolation of hindcast and/or measured data to 1% annual chance values should be documented, including comparisons between alternate procedures if appropriate.

The Mapping Partner shall document all wave generation assumptions used in modeling and parametric approaches, including the nature of data used to define winds (speeds, directions, duration) and bathymetry (including the 100-year water-level determination). The documentation shall include any approximations or assumptions used in the analysis. When observational data, such as wave buoy data, are available, the wave height, period, and spectral parameters should be compared to the model output.

The Mapping Partner shall document the assumptions, methods, and results of all analyses of wave transformation conducted for the FIS. This documentation should include selection of offshore and nearshore points, source of transformation coefficients, any special assumptions regarding local transformation processes such as sheltering and reflection, and so forth. If a spectral wave model is applied for nearshore transformation determination, all modeling factors should be sufficiently documented, so the modeling effort could be reproduced if necessary. If a field effort is undertaken to validate transformation models, the field work shall be summarized in detail, including times and locations of all observations, general conditions at the time of the work, a full description of all equipment and procedures, and a summary of all data in archival form. All study output should be documented and summarized in a format suitable for subsequent flooding analyses including setup, runup, overtopping, and erosion.

D.4.4.2 Water Levels

D.4.4.2.1 Overview

The two fundamental components of the Base Flood Elevation (BFE) are *water levels*, discussed in this subsection, and waves, discussed in the previous subsection. The still water level (SWL) is the base elevation upon which the waves ride. It consists of several parts including mean sea level (MSL), the astronomic tide that fluctuates around MSL, the El Niño fluctuation, and storm surge. All storm wave contributions are excluded; static wave setup (Section D.4.5) contributes to the *mean water level* (MWL), somewhat higher than the SWL.

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

D.4.4.2.2 Astronomic Tide

D.4.4.2.2.1 Tides and Tidal Datums

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

The tides along the Pacific Coast are mixed and semi-diurnal, meaning that there are two highs and two lows each day; conventionally, mixed tides are semi-diurnal tides for which the magnitudes of successive highs or successive lows have large variation. The average of all the highs is denoted as mean high water, MHW, while the average of all the lows is *mean low water* (MLW). Averages are taken over the entire tidal datum *epoch*, which is a particular 19-year period explicitly specified for the definition of the datums; a full astronomic tidal cycle covers a period of 18.6 years. The average of all hourly tides over the epoch is the MSL.

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

These several levels are important because they constitute the datums to which tide data have traditionally been referred. Local charts and recorded tide gage data are generally referenced to local MLLW. This introduces some ambiguity because MLLW varies from place to place and from epoch to epoch. For use in FISs, then, these tidal datums are insufficient in themselves, and must be related to a standard vertical datum, North American Vertical Datum (NAVD) or National Geodetic Vertical Datum (NGVD); it is not always straightforward to make this connection. However, NOAA maintains tidal benchmarks for many stations that are now tied to a standard vertical datum. Benchmark sheets are available at NOAA's site, <http://co-ops.nos.noaa.gov/bench.html>. The following example is extracted directly from the Los Angeles benchmark sheet:

```
Tidal datums at LOS ANGELES, OUTER HARBOR based on:
     LENGTH OF SERIES:      19 Years
     TIME PERIOD:           January 1983 - December 2001
     TIDAL EPOCH:           1983-2001
     CONTROL TIDE STATION:

Elevations of tidal datums referred to Mean Lower Low Water (MLLW), in
METERS:
     HIGHEST OBSERVED WATER LEVEL (01/27/1983)    =  2.384
     MEAN HIGHER HIGH WATER (MHHW)                =  1.674
     MEAN HIGH WATER (MHW)                        =  1.449
     MEAN TIDE LEVEL (MTL)                        =  0.868
     MEAN SEA LEVEL (MSL)                         =  0.861
     MEAN LOW WATER (MLW)                         =  0.287
     NORTH AMERICAN VERTICAL DATUM-1988 (NAVD)    =  0.062
     MEAN LOWER LOW WATER (MLLW)                  =  0.000
     LOWEST  OBSERVED WATER LEVEL (12/17/1933)    = -0.832

Bench Mark Elevation Information            In METERS above:
     Stamping or Designation                MLLW        MHW
     8-14 FT ABOVE MLLW                      4.194    2.746
     WILMINGTON D9A 1954                     2.967    1.518
     WILMINGTON D10B 1954                    2.832    1.383
     11 1935 RESET 1967                      4.711    3.263
     NO 13 1971                              4.147    2.698
     A 1296 1977                             3.167    1.718
     0660 N 1977                             3.553    2.104
     10 1930 RESET 1985                      3.101    1.653
     NO 14 1971                              4.068    2.619
     0660 P 2000                             4.252    2.803
```

In this example, NAVD is shown to be at 0.062 meters above MLLW for the specified 1983-2001 epoch, fixing the tidal datums. Not all benchmark sheets include NAVD (or NGVD) as this example does, but most include surveyor's benchmark information as shown above, through which the tidal datums can usually be tied to a standard vertical datum as needed in FISs; these benchmark sheets include full descriptions of the benchmarks and exact locations.

D.4.4.2.2.2 Tide Observations

The tide is recorded at a large number of gages maintained by NOAA, with records dating back over 100 years in some cases. Much of these data are available at NOAA's website, <http://www.co-ops.nos.noaa.gov/data_res.html>, as either six-minute or hourly time series over the particular site's entire period of record. Additional data may be available from NOAA, USACE, or others.

The tide observations record the total water level at the gage, suitably filtered to suppress high frequency wave components, leaving the long period components associated not only with astronomic tide, but also with sea-level fluctuations caused by atmospheric pressure fluctuations (sea level can change by about 1 foot for each 1 inch of change in barometric pressure), El Niño variations, wind setup (storm surge), riverine rainfall runoff into a relatively confined tide gage site, low frequency tsunami elevation, and wave setup to the degree that it exists at the gage site. In general, little wave setup is reflected in tide gage data because gages may be located in protected areas not subject to much setup, or in open areas outside the surf zone, and so seaward of the largest setup values (see Subsection D.4.5.1 for discussion of the physics of setup).

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

D.4.4.2.2.3 Tide Predictions

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

The NOAA website also provides tide predictions for any date in the past or future, limited however to one year of predictions at a time. Note that these predictions are computed using the currently adopted values of the 37 tidal constituents for the site.

The Mapping Partner should obtain NOAA's tide prediction computer program, NTP4, and generate tide predictions as needed. The advantages include not only convenience, but more importantly, the ability to use other constituent values than those currently adopted. This is important because the local tide depends not only on the astronomic forcing, but also on the response of the local basins. The response can, and does, change with time owing to siltation and dredging, construction of coastal structures such as breakwaters, changes in inlet geometry, and so forth. Consequently, the astronomic tide observed at a fixed location may not be stationary, but may have changed over the period of record. NOAA can provide previous estimates of the tidal constituents for a site, and these should be used with the NOAA computer program to produce more realistic predictions than would be achieved using only the current data for a prior period.

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

Finally, there may be some ambiguity or uncertainty in tide prediction associated with El Niño fluctuations. As discussed elsewhere, the El Niño effect causes periodic rise and fall of coastal sea levels, and these are inevitably incorporated in the data from which the tidal constituents are determined. The same is true for sea-level fluctuations associated with barometric fluctuations, although El Niño effects are more persistent. It is expected, then, that to some degree the determination of tidal constituents has been confounded by El Niños. The affected constituents would be those with periods comparable to characteristic El Niño fluctuation periods. The phasing of the El Niño fluctuation and the selected tidal epoch would influence the manner and extent to which these processes would then appear intermingled; estimates of tidal constituents obtained from short duration observations might be especially vulnerable in this regard because a long period of observation may effectively smooth the El Niño contribution toward a null average. Nevertheless, for FIS applications, the Mapping Partner shall assume that the tidal constituents do not include non-astronomic components.

D.4.4.2.2.4 Extraction of Non-astronomic Still Water from Gage Records

As discussed above, both observed data and a method to predict the purely astronomic component of those observations are available. By subtracting the predictions from the observations, one arrives at a time series of the non-astronomic contribution to the measured still water, including surge and meteorological effects, El Niño levels, rainfall runoff, and tsunamis – in fact, all non-astronomic components termed *still water*. As a practical matter, the static setup will not usually be present in the record to a significant degree, for reasons already mentioned. Figure D.4.4-12 shows measured and predicted tides at Crescent City for a five-day period in 1983. As shown, superimposed on the fluctuating astronomic tide is a slowly varying residual component approximately 2 feet in amplitude.

The recommended procedure to extract still water statistics from the difference between the observed and predicted data is extremely simple in concept, assuming that the period of record is significant (30 years or more) and that the older predictions were made using the appropriate set of tidal constituents, *not* necessarily those in current use. One first determines the differences between the observed and predicted elevations of the highs and lows, and then scans these to locate the annual peaks. These annual peaks are used to fit an extreme value distribution, from which the 1% annual chance elevation can be found.

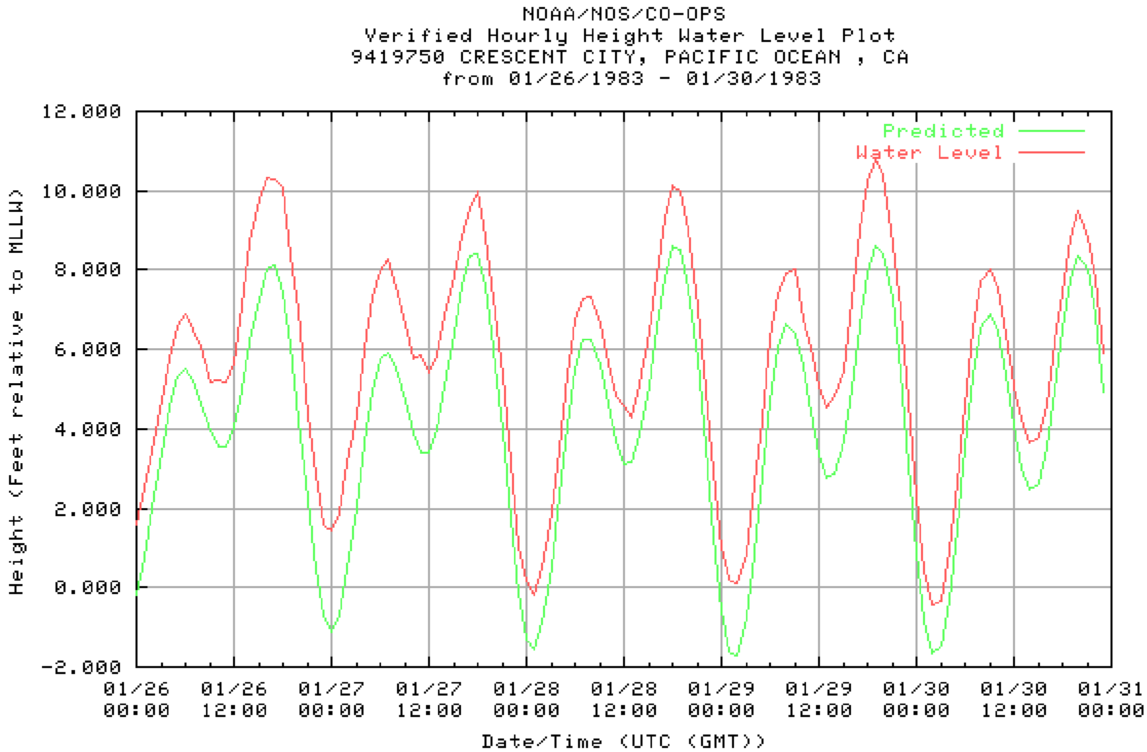

Figure D.4.4-12. Predicted and Observed Tides at Crescent City, California

As discussed in Subsection D.4.3.3, an acceptable approach is to adopt the Generalized Extreme Value (GEV) Distribution, and to determine the distribution parameters by the method of maximum likelihood. An example is shown in Section D.4.3. The Mapping Partner may consider other distributions and other fitting techniques although the particular result with the greatest likelihood value among all of the considered distribution types should be adopted, unless otherwise approved by the FEMA study representative.

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

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

D.4.4.2.3 Surge

D.4.4.2.3.1 General Considerations

Storm surge is the rise of the ocean surface that occurs in response to barometric pressure variations (the inverse barometer effect) and to the stress of the wind acting over the water surface (the wind setup component). Wave setup is excluded by this definition. Setup is not incorporated in the established procedures for storm surge modeling, nor is it present to a significant degree in tide gage data owing to the typical configuration of gages with respect to the zone of large setup; consequently, it must be taken into account separately as discussed in Subsection D.4.5.1.

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

Guidance for complex 2-D modeling is best obtained from the user's manual for a particular model. However, to aid the Mapping Partner in model selection, a supporting document (*Surge Modeling Overview*) has been prepared as a supplement to these guidelines. It briefly addresses storm surge modeling from a numerical hydrodynamic perspective, so a Mapping Partner can evaluate the adequacy of candidate storm surge models. The discussion can help the Mapping Partner assess strengths and weaknesses of programs and assist in the selection of an appropriate model by identifying important model features and capabilities.

It is recognized, however, that surge on the Pacific Coast is relatively small compared to wave effects and to surge on the Atlantic and Gulf coasts. Consequently, a complex and expensive 2-D modeling effort should seldom be necessary, and should be considered only after discussion with the FEMA study representative. The simpler 1-D surge modeling method discussed in the following section is usually adequate for the Pacific Coast.

D.4.4.2.3.2 Simplified 1-D Surge Modeling

The generally narrow continental shelf and the lower winds that prevail on the Pacific Coast result in a lesser wind-induced surge than on the Atlantic and Gulf of Mexico coastlines, which are attacked by hurricanes. Consequently, satisfactory estimates of open coast surge on the Pacific can usually be obtained using methods far simpler than the full 2-D approach. There are several reasons a Mapping Partner might wish to make such estimates: the Mapping Partner may wish to determine SWL in regions where an absence of tide gage data makes it impractical to extract still water data from the tide residual; the Mapping Partner might wish to compare the surge level from a wind of a certain magnitude with the 1% annual chance wave event; or the 1%

annual chance wave event might be accompanied by strong onshore winds and the Mapping Partner might wish to include this contribution or to evaluate the significance of neglecting it.

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

The System of Interest and Governing Equations

The system of interest is shown in Figure D.4.4-13. A wind with speed *W* is directed at an angle, θ, to the *x*-axis that is parallel to the shoreline. The surge distribution is $\eta\ (y)$, where *y* is the cross-shore direction. The wind obliquity induces a mean current, *U*(*y*,*t*), which varies with time, *t*.

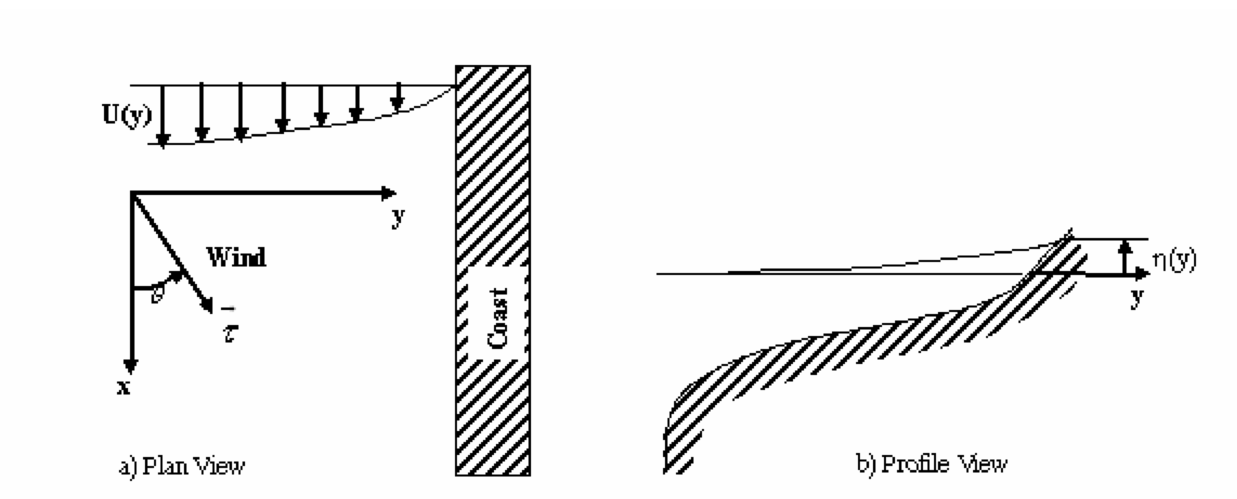

Figure D.4.4-13. Definition Sketch for the BST Formulation

The governing equations are:

y Direction

$$\frac{\partial \eta}{\partial y} = \frac{1}{g}\left(\frac{n\tau_y}{\rho(h+\eta)} - f_c U\right) \qquad \text{(D.4.4-22)}$$

x Direction

$$\frac{\partial U}{\partial t} = \frac{1}{h+\eta}\left(\frac{\tau_x}{\rho} - \frac{fU^2}{8}\right) \qquad \text{(D.4.4-23)}$$

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

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

$$\begin{Bmatrix} \tau_x \\ \tau_y \end{Bmatrix} = \begin{Bmatrix} \cos\theta \\ \sin\theta \end{Bmatrix} k|W|W \qquad \text{(D.4.4-24)}$$

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

$$k = \begin{Bmatrix} 1.2x10^{-6}, \quad |W| \le W_c \\ 1.2x10^{-6} + 2.25x10^{-6}\left(1 - \dfrac{W_c}{|W|}\right)^2 \ |W| > W_c \end{Bmatrix} \qquad \text{(D.4.4-25)}$$

Program Input and Output

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

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

The program is extremely efficient and easy to use, with minimal input requirements. The necessary bathymetric data can be obtained from available charts, and wind data can usually be extracted from the GROW database, which includes wind speed and direction over a GROW cell at 3-hour intervals for the duration of the record. The wind values are representative of the entire cell; if finer resolution is thought to be needed (for example, to account for sheltering), then the Mapping Partner should attempt to obtain supplementary wind data from the National Weather Service (NWS), local airports and agencies, and so forth. Tide boundary condition data can be obtained from tide tables, from the NOAA website, or using the NOAA prediction program, NTP4.

A second simplified tool, the DIM program discussed in Section D.4.5, is also available. It was developed especially for the computation of setup over a shore normal transect similar to that used here by BATHYS. DIM requires additional input, however, because its primary purpose is wave setup simulation. The user's manuals for these programs should be consulted for additional details and examples of use.

D.4.4.2.3.3 Surge Estimation from Tide Data

A procedure was outlined in Subsection D.4.4.2.2.4, to extract the total still water, exclusive of astronomic tide, from a tide gage record. It is in general difficult or impossible to distinguish among the several components of the residual, including surge, and there is usually no need to do so. Consequently, the tide residual methodology can be considered equivalent to the estimation of surge from tide data, for all practical purposes. What one generally wants is the 1% annual chance level of the total flood, irrespective of mechanism.

D.4.4.2.4 Water Levels in Sheltered Waters

D.4.4.2.4.1 Overview

Water levels and wave propagation in sheltered waters may be influenced by a variety of factors that can alter coastal flood characteristics. Incoming storm surge and the resulting extreme still water elevations along the shorelines of sheltered waters may achieve higher elevations than at adjacent open coast locations owing to channelization and tidal amplification controlled by the orientation, geometry, and bathymetry of the basin; lower elevations may occur if restrictive tidal inlets impede the incoming tide. Small basins may also experience higher water levels from the contributions of direct precipitation and runoff, or from resonant basin oscillations called *seiche*.

Recorded tide elevations may require transposition from the tide gage to a flood study site within sheltered waters, to better represent the local still water elevation during the 1% annual chance flood event. Guidance for evaluating and applying tide gage data to ungaged locations is provided in this subsection.

As waves propagate into sheltered water from the open coast, additional wave transformations may occur. Tidal inlets are a significant feature that controls the entry and propagation of waves into inland waters; guidance is provided on inlet characteristics and effects. Other characteristics of sheltered waters that may lead to additional wave transformations include, but are not limited to, the presence of tidal and fluvial currents, channel shoaling, navigation structures, and vegetation.

In general, detailed numerical modeling may be the most appropriate method for estimating water levels and wave transformations in these complex coastal settings. However, simpler techniques may be used if small-scale localized effects do not lend themselves to large-scale modeling, or if the Mapping Partner wishes to make preliminary estimates of the relative importance of processes before proceeding to more detailed evaluations.

D.4.4.2.4.2 Variability of Tide and Surge in Sheltered Waters

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

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

Some simple empirical evidence may permit an approximate evaluation of these variations:

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

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

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

Tides and storm surges propagating into sheltered water areas undergo changes controlled by frictional effects and basin geometry. The Mapping Partner must evaluate the differences between the physical settings of the nearest tide gage(s) and the study site, and the distance and hydraulic characteristics of the intervening waterways between these locations to establish a qualitative understanding of the potential differences in tidal elevations between the gaged and ungaged locations. If flood high water marks are available in the vicinity of the ungaged sheltered water study site, these elevations shall be compared to recorded tide elevations to correlate surge components of the tidal still water between locations. In general, surge data are of more limited availability than tide data. It may sometimes be reasonable to assume similarity between surge and tide, and so infer surge variation from known tide variation. The validity of such inference is limited, however, by differences in amplitude and duration of high water from the two processes, and by the fact that tide is cyclic and so may not vary in the same manner as a single surge wave.

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

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

1. Apply the CEM methods and nomograms in reverse to estimate the adjacent open coast annual maximum still water elevations (astronomical tide elevation plus storm surge height) based on recorded still water elevations from a primary tide gage in the sheltered water body closest to the flood study site. The physical setting of a primary tide gage may be such that recorded tide elevations are representative of open coast tide elevations; however, this condition should not be assumed.

2. Using the estimated open coast tide elevation, reapply the CEM methods and nomograms (in forward mode) to estimate the associated annual maximum still water elevations in the ungaged sheltered water body where the study site is located. Use of the same open coast still water elevation between the gaged and ungaged sheltered water areas is acceptable if it can be assumed that the annual extreme still water elevations are generated from regional storm systems large enough in spatial extent to encompass the two locations.

When tidal elevations are to be established in an ungaged sheltered water body, it is recommended that a limited tidal monitoring program be undertaken to estimate tidal datums near the study site. NOAA (2003) provides guidance on methods and computational techniques for establishing tidal datums from a short series of record. The accuracy of the resulting datums on the West Coast can range from 0.13 foot for a one-month series of data to 0.06 foot for a 12-month series (NOAA, 2003); a short-term effort will usually be entirely adequate for use in a FEMA FIS.

The complex shorelines and bathymetry of sheltered waters may lead to significant changes in tide characteristics. The objective of short-term monitoring should be to provide observed data from which tidal datums may be estimated to check the accuracy of subsequent higher elevation estimates of extremal still water elevations in ungaged sheltered water areas and, in turn, to increase the level of confidence in the resulting flood hazard elevations.

Irrespective of the approach taken, the Mapping Partner shall evaluate the physical setting of the tide gage(s) from which data are used. Observation of the gage setting may provide insight to the relative degree of sheltering or other characteristics of a given tide gage. Information on NOAA tide gages can be obtained from the Internet at <http://www.co-ops.nos.noaa.gov/usmap.html>. Mapping Partners shall also determine if a tidal benchmark has been established near the flood study site (<http://www.co-ops.nos.noaa.gov/bench.html>). Tidal benchmarks are elevation reference points near a tide gage to which tidal datums are referenced. Some tidal benchmarks are now tied to the NAVD88, or to the earlier NGVD29, providing an appropriate vertical elevation reference. Benchmark elevations may become invalid over time if changes occur in local tide conditions because of dredging, erosion, or other factors (NOAA, 2000a); the Mapping Partner shall review the publication date of the data together with information concerning any recent changes in the vicinity of the tide gage setting to ensure the data are accurate.

If the physical setting and tidal processes of a coastal flood study site are particularly complex and the application of the simple methods described in the CEM are questionable, the Mapping Partner is encouraged to consult with the NOAA NOS <http://co-ops.nos.noaa.gov/index.html> for further guidance on estimating tidal and surge elevations at ungaged sites (USACE, 1986).

Tidal Inlets

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

Seiching

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

The amplitude of seiche is usually small; the primary concern is often with the associated currents that can cause large excursions and damage to moored vessels if resonance occurs. However, surface elevations and boundary flooding in an enclosed basin may become pronounced if the incoming wave excitation contains significant energy at the basin's natural seiche periods. The Mapping Partner shall investigate the likelihood of seiche under extreme water-level and wave conditions. Bathymetry, basin dimensions, and incoming wave characteristics should be reviewed to determine the potential for seiching; the CEM (Section II-5-6) provides background and guidance for estimating the natural periods of open and closed basins. Numerical models are most appropriate for evaluating the effects of long waves in enclosed basins and shall be considered for use in a sheltered water study if seiching is believed to have the potential to contribute significantly to boundary flooding during the 1% annual chance flood condition.

D.4.4.2.4.3 Documentation

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

D.4.4.2.5 Water Levels During El Niños

The El Niño/La Niña process produces substantial variation in SWLs along the Pacific Coast, with anomalies persisting for long periods. These variations are the result of large-scale oceanographic changes associated with changes in the equatorial trade wind patterns. The result of interest here is the creation of very large-scale non-tidal sea-level fluctuations extending over oceanic distances.

As summarized in a supporting document for these guidelines prepared by Komar and Allen (2004), El Niño conditions begin with the periodic cessation of the Pacific trade winds, allowing the sea surface slope to change, and producing an eastward flow of warm water along the equator. Upon reaching the South American coast, this flow splits into components traveling both north and south, affecting the entire Pacific Coast as far north as Alaska. Eventually, tradewind conditions reestablish in the Pacific and conditions reverse, initiating the La Niña phase.

The time scale of these processes is indicated in Figure D.4.4-14 in which the Multivariate ENSO Index (MEI) is a derived unit incorporating multiple meteorological parameters related to El Niño variation; the shaded band represents the threshold for event identification.

The significant El Niños of 1982 and 1997 are evident; these events raised water levels along the Pacific Coast by 1 to 2 feet in some areas, persisted for long periods, and contributed to extreme erosion at many sites (see Komar and Allen, 2004, for a survey of those effects).

The contribution of the El Niño process to the statistics of still water is thought to be fully reflected in tide gage data, and so forms a portion of the tide residual discussed earlier. Still water estimates derived from tide gage data can be assumed to properly reflect this process, although it has been pointed out that tide predictions may contain a portion of El Niño effect because the tidal constituents are determined empirically. Nevertheless, the Mapping Partner shall consider how specific El Niño/La Niña episodes might affect interpretation of the historical record, and how particular data observed during the El Niño/La Niña extremes should be interpreted.

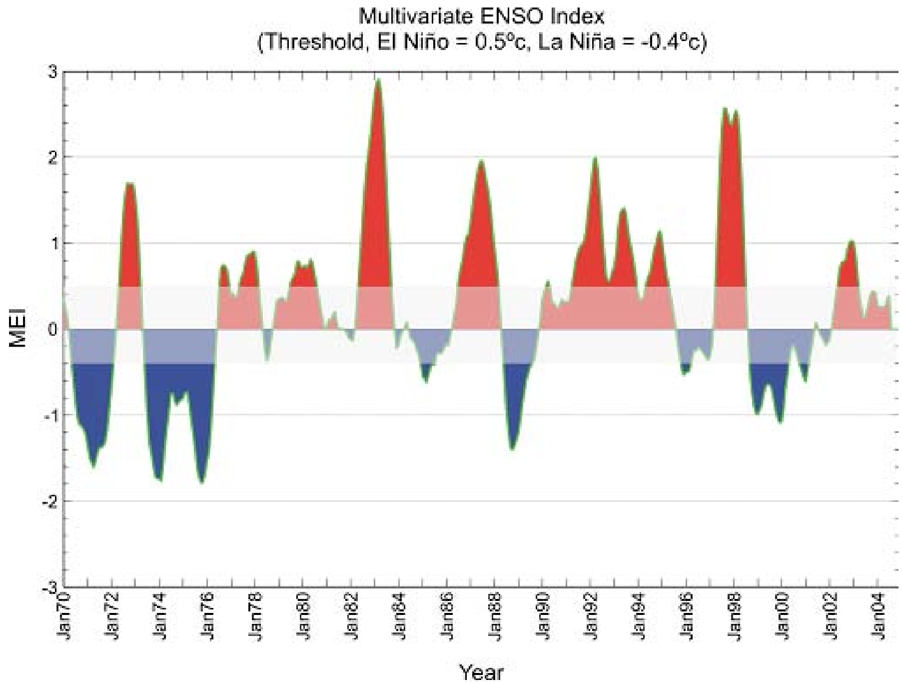

Figure D.4.4-14. El Niño Fluctuations since 1970 (Komar and Allen, 2004)

D.4.4.2.6 1% Annual Chance Still Water Levels

The 1% annual chance flood on the Pacific Coast is seldom the result of still water alone; other processes such as wave runup or tsunamis ride atop the still water, which serves as a base. The exception might be well-sheltered areas, protected from waves and affected only by the high SWLs associated with tide, surge, and El Niño fluctuations; even in such areas, however, the total 1% flood level may include a physically independent contribution from rainfall runoff.

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

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

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

D.4.4.2.6.1 Tide Statistics

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

D.4.4.2.6.2 Surge Statistics

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

The second way in which surge 1% levels are determined is through numerical modeling of surge elevation using 1-D or 2-D models, as discussed above, combined with a statistical model relating the surge simulations to storm frequency and storm parameter distributions. Three ways of doing this have been used: the Joint Probability Method (JPM), which has been used in many FISs on the Atlantic and Gulf coasts in combination with the FEMA Storm Surge Model; the more recent Empirical Simulation Technique (EST), which has been used in combination with the ADCIRC model for recent studies; and a Monte Carlo approach, which has been used for coastal setback determinations in the State of Florida, and which is particularly suited for use with the 1-D surge model, BATHYS, described previously. Because the surge levels on the Pacific Coast are generally small compared to the Atlantic and Gulf coasts, it is not expected that JPM and EST studies with large 2-D surge models are often necessary. The 1-D BATHYS model with Monte Carlo simulation, or – more directly – with direct simulation of the wind record using, say, GROW data, should be adequate in most cases. Brief descriptions of the JPM, EST, and Monte Carlo methods are given in Section D.4.3.

For Pacific Coast applications, an alternate method of 1% surge estimation may be considered; it is the most straightforward and simplest method of all. This is to perform a direct simulation of the local wind record using available wind data, such as the GROW data, for example, which specifies wind speed and direction at 3-hour intervals over the entire record of more than 30 years. This is a feasible task owing to the efficiency of the 1-D BATHYS model (or the alternative DIM model discussed in Section D.4.5).

Tide can be very simply accounted for by adopting the predicted tide as the offshore boundary condition. For each year of simulation, the peak surge should be stored; an extremal analysis using these annual peaks then gives the required surge statistics.

Use of this approach should be first approved by the FEMA study representative. Some small revision of the 1-D model could be made to read both wind and tide (for arbitrarily long durations) from separate input data files, and to automatically store annual peaks for the frequency analysis. As with the storm-by-storm simulation, the Mapping Partner shall make a critical assessment of the wind data before considering this approach. GROW data are representative of a relatively large cell and may not reflect important local factors such as sheltering by islands; other, more local, data may be required.

D.4.4.2.6.3 El Niño Statistics

No separate account of El Niño statistics is suggested. The pertinent El Niño effects are embedded in available data, such as tide gage still water data (incorporating the effect of El Niños on ocean level) and GROW wave data (incorporating the meteorological effects) , and so will be automatically taken into account for in any analyses made using those data resources. For most purposes, the El Niño contribution may be assumed to be part of the surge estimate obtained from the tide gage residuals.

D.4.4.2.6.4 Combined Effects: Surge Plus Tide

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

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

First, if the surge and tide can be assumed to combine linearly (that is, neither is physically altered by the presence of the other), then the simplest method is to simply add them in some manner. If a surge episode is relatively long compared with a tidal cycle, then high tide will be certain to occur at some time for which the surge is near its peak, and a simple sum of amplitudes may be sufficiently accurate.

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

A third, slightly more accurate approach but still assuming physical independence, is based on the convolution method mentioned in Section D.4.3. In this method, the probability density functions for both tide and surge without tide are used. Previous discussion has shown how both of these may be established. If the probability density of the tide level Z is denoted by $p_T(Z)$ and the probability density of the surge level is $p_S(Z)$, then the probability density of the sum of the two is given by:

$$p(Z) = \int_{-\infty}^{\infty} p_T(T)\, p_S(Z-T)\; dT = \int_{-\infty}^{\infty} p_T(Z-S)\, p_S(S)\; dS \qquad \text{(D.4.4-26)}$$

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

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

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

D.4.4.2.6.5 Combined Effects: Surge Plus Riverine Runoff

The final instance of combined still water frequency to be described concerns the determination of the 1% SWL in a tidal location subject to flooding by both coastal and riverine mechanisms. This is the case in the lower reaches of all tidal rivers.

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

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

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

The procedure is shown schematically in Figure D.4.4-15, in which the combined curve has been constructed by addition of the rates at elevations of 6, 8, 10, and 12 feet. The entire procedure can be implemented in a simple calculator program, with the input at point P being the 10-, 50-, 100-, and 500-year levels for both runoff and surge, as obtained from standard FIS tables.

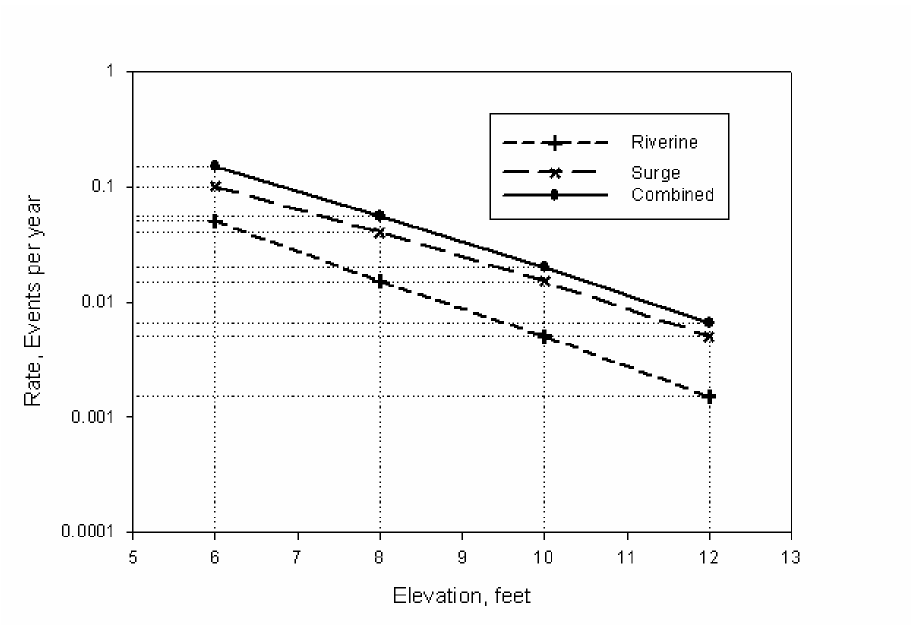

Figure D.4.4-15. Schematic Illustration of Riverine and Surge Rate Combination

D.4.4.2.7 Non-Stationary Processes

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

The appropriate time window for FISs is established by the period of record covered by the available hydrologic data on the one hand, and the probable lifetime of a particular study, on the other. Consider El Niños, discussed above. Viewed for a period of a small number of months or years, the El Niño phenomenon appears to be a decidedly unsteady process during which ocean levels rise, and other environmental changes occur. However, when seen at a scale of about 15 years or more, the El Niño variations appear to be more or less steady fluctuations, mirrored by the opposite La Niña phases, and showing no evident non-stationary trends. Examining observations over a short interval, say 5 years or less, may require recognition of a temporary lack of stationarity, whereas a record covering multiple cycles of El Niño, such as long-term tide gage data and the GROW wave data, may properly reflect the effects of the fluctuation, without requiring any special consideration of non-stationarity. This is characteristic of time series: it is difficult or impossible to discern whether an observed change is the result of a trend or is merely a temporary fluctuation.

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

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

D.4.4.2.7.1 Relative Sea Level – Sea-level Rise

Sea level rise appears to be a real, long-term effect observed all along the U.S. coastline. For the majority of the Pacific Coast, the rate of rise is between 0 and 3 millimeters per year, or up to about 1 feet per century; see, for example, data available from NOAA at its website <http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml>. The Philadelphia District of the USACE maintains a useful collection of sea-level rise links at their website <http://www.nap.usace.army.mil/cenap-en/slr_links.htm>. There is also a very large set of sea-level trend data for individual stations along the Pacific Coast, which can be obtained from the referenced NOAA site.

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

D.4.4.2.7.2 Relative Sea Level – Land Subsidence

Land subsidence produces the same sort of effect as sea-level change – a rise in the apparent sea level – but subsidence might be much the more significant factor in a local area. For example, portions of the Sacramento-San Joaquin Delta have subsided by more than 15 feet since reclamation for agriculture began in the 19th century. Many areas in Southern California have subsided by several feet as a result of gas, oil, or water extraction over the past few decades.

Such large displacements make it imperative that historical data be interpreted with caution. The Mapping Partner must ensure that gage datums have been properly adjusted over time so that water-level records, benchmarks, observed highwater marks, and all similar data are properly interpreted.

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

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

D.4.4.2.7.3 Astronomic Tide Variation

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