Map MODERNIZATION

Federal Emergency Management Agency

FEMA's Flood Hazard Mapping Program

# Guidelines and Specifications for Flood Hazard Mapping Partners

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## *Appendix D: Guidance for Coastal Flooding Analyses and Mapping*

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FINAL

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# Appendix D

# Guidance for Coastal Flooding Analyses and Mapping

## D.1 General Guidance

A variety of analytical methodologies may be used to establish Base Flood Elevations (BFEs) and floodplains throughout coastal areas of the United States. These methodologies are too voluminous to be included in these Guidelines. This Appendix itemizes references for the methodologies currently in use by FEMA for specific coastal flood hazards, provides general guidance for documentation of a coastal flood hazard analysis, specifies flood hazard analysis procedures for the Great Lakes coasts, and outlines intermediate data submissions for coastal flood hazard analyses with new storm surge modeling and revised stillwater flood level (SWFL).

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### D.1.1 Coastal Flood Hazard Analysis Methodologies

The publications cited below were prepared for, and are available from, FEMA, or they are used to prepare a coastal flood hazard assessment and establish BFEs. The publications prepared for FEMA will be provided to the Mapping Partners responsible for performing coastal flood hazard analyses. The Mapping Partners responsible for final production of Flood Insurance Studies (FISs) for the Atlantic Ocean, Gulf of Mexico and Great Lakes shall obtain copies of the published data used to prepare the coastal flood hazard analyses and establish BFEs, and shall be familiar with the use and application of the information presented in the publications cited below. Mapping Partners responsible for final production of FISs for the Pacific Ocean coastal areas shall consult with the appropriate FEMA Regional Project Officer (RPO) to determine the appropriate methodologies that shall be followed.

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**Northeaster Flooding**

Stone & Webster Engineering Corporation, "Development and Verification of a Synthetic Northeaster Model for Coastal Flood Analysis," 1978.

U.S. Department of the Army, Corps of Engineers, New England Division, Hydraulics and Water Quality Section, "Tidal Flood Profiles, New England Coastline," September 1988.

**Hurricane Flooding**

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States (NWS 38),* April 1987.

Federal Emergency Management Agency, *FEMA Coastal Flooding Storm Surge Model*, Volumes 1, 2, and 3, August 1988.

**Pacific Northwest Storm Flooding**

CH2M HILL, Inc., "Determination of Flood Levels on the Pacific Northwest Coast for Federal Insurance Studies," *Journal of Hydraulics Division, ASCE*, D. E. Dorratcague, J. H. Humphrey, and R. D. Black, 1977, Vol. 103, 73–81.

U.S. Department of the Army, Corps of Engineers, Pacific Ocean Division, *Manual for Determining Tsunami Runup on Coastal Area of Hawaii*, August 1978.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Technical Report H-80-16, *Tsunami-Wave Elevation Predictions for American Samoa*, September 1980.

**Tsunami Flooding**

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Technical Report H-77-16, *Tsunami-Wave Elevations, Frequency of Occurrence for the Hawaiian Islands*, August 1977.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Technical Report CERC-87-7, *Tsunami Predictions for the Coast of Alaska, Kodiak Island to Ketchikan*, April 1987.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Technical Report H-80-16, *Tsunami-Wave Elevation Predictions for American Samoa*, September 1980.

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U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Technical Report HL-80-18, *Type 19 Flood Insurance Study: Tsunami Predictions for Southern California*, 1980.

U.S. Department of the Army, Corps of Engineers, Pacific Ocean Division, *Manual for Determining Tsunami Runup on Coastal Area of Hawaii*, August 1978.

**Great Lakes Mapping of Coastal Flooding Areas**

U.S. Department of the Army, Corps of Engineers, *Revised Report on Great Lakes Open-Coast Flood Levels*, *Phases I and II*, April 1988.

U.S. Department of the Army, Corps of Engineers, *Great Lakes Wave Runup Methodology Study*, June 1989.

Federal Emergency Management Agency, *Guidelines for Great Lakes Wave Runup Computation and Mapping*, June 1991.

Dewberry & Davis, *Basic Analyses of Wave Action and Erosion with Extreme Floods on Great Lakes Shores,* Draft Report, October 1995.

Federal Emergency Management Agency, *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping – Great Lakes,* Draft Report, August 1996.

**Mississippi River Delta Flooding**

Joseph N. Suhayda, *Attenuation of Storm Waves over Muddy Bottom Sediments*, August 1984.

**Wave Height and Runup Analyses**

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

Federal Emergency Management Agency, *Assessment of Current Procedures Used for the Identification of Coastal High Hazard Areas (V Zones)*, September 1986.

Federal Emergency Management Agency, *Basis of Assessment Procedures for Dune Erosion in Coastal Flood Insurance Studies*, January 1989.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center, WIS Report 19, *Hurricane Hindcast Methodology and Wave Statistics for Atlantic and Gulf Hurricanes from 1956-1975*, April 1989.

Federal Emergency Management Agency, *Wave Height Analysis for Flood Insurance Studies (Technical Documentation for WHAFIS Program Version 3.0)*, September 1988, amended with software, July 1989.

Federal Emergency Management Agency, *Wave Runup Model Version 2.0 (RUNUP 2.0), 1991*.

This Document is Superseded.
For Reference Only.

U.S. Department of the Army, Corps of Engineers, *Shore Protection Manual, Volumes I and II,* 1984.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, *Automated Coastal Engineering System*, Version 1.07, September 1992.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center, WIS Report 20, *Southern California Hindcast Wave Information*, December 1992.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center, WIS Report 30, *Hindcast Wave Information for the U.S. Atlantic Coast*, March 1993.

**Evaluation of Coastal Structures**

U.S. Department of the Army, Corps of Engineers, *Shore Protection Manual, Volumes I and II,* 1984.

U.S. Department of the Army, Corps of Engineers, *Design of Coastal Revetments, Seawalls and Bulkheads*, April 1985.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Technical Report CERC-89-15, *Criteria for Evaluating Coastal Flood Protection Structures*, December 1989.

**Atlantic and Gulf Mapping of Coastal Areas**

Federal Emergency Management Agency, *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping*, Final Draft, March 1995.

[February 2002]

## D.1.2 Study Documentation

Mapping Partners responsible for producing coastal FISs must document fully the coastal flood hazard determination for each study. This documentation shall identify the methodology employed as well as the computational approach and the input data used in the calculation of the coastal flood elevations. The technical specifications under which all coastal FISs will be documented are provided in the various internal and public FEMA reports outlining the approved coastal storm surge elevation methodology that are referenced in Subsections D.1.1 and D.1.4. These reports include algorithms, computer codes, guidelines for model use, and examples of model runs.

Although some of these reports provide relatively specific information on both the general procedures to be employed in processing the meteorological and hydrologic data, and the specifics of the hydrodynamic and windfield models to be employed, the reports contain no information on the application of the methodology to a particular coastal site. Therefore, the Mapping Partner responsible for performing a coastal study shall document the specific meteorological and hydrologic data, ocean bathymetry, shoreline characteristics, surface and bottom friction coefficients, and other parameters used in the particular model application. For this purpose, the Mapping Partner shall produce an engineering report for each coastal study.

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The purpose of the engineering report is to provide the detailed site-specific data needed by FEMA and the affected coastal communities to reconstruct or defend, on technical grounds, the study results. In general, the documentation shall include the input data; modeling approach; model parameter values; and all assumptions, decisions, and judgments that influence model outputs. The material to be included in the engineering report is summarized in the subsections below. Although the emphasis is on coastal studies incorporating storm surge models, Mapping Partners using other methods shall nonetheless adhere to the appropriate subsections. The Mapping Partner performing a coastal study shall obtain RPO approval for any deviations from the requirements documented in these Guidelines.

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### D.1.2.1 Introductory Material

In the first section of the engineering report, the Mapping Partner shall describe the geographic setting of the study site, discuss the local surge-producing climatology of both tropical and

extratropical storms, and provide a history of extreme storm surges. The Mapping Partner shall also report on unique aspects of each component of the stillwater flood elevation (SWEL) that was investigated (e.g., inverted barometer setup, wind transport, astronomical tide level, pre-surge anomaly, wave action, and abnormal hydrological conditions). The Mapping Partner also shall include a short discussion of the coastal study results and how they will be used in producing the Flood Insurance Rate Map (FIRM).

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### D.1.2.2 Outline of Methodology

In the second section of the engineering report, the Mapping Partner shall provide an outline of the basic technical approach employed in the study. Topics to be covered include identification of the storm (wind) model, the hydrodynamic model, and the statistical procedure used to determine flood frequencies. The purpose of this section is to outline the relationship between the technical material to be covered in the main body of the engineering report and the basic methodological approach used in the study. This outline should be logically organized and sufficiently complete so that the detailed documentation that follows can be easily read and understood.

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### D.1.2.3 Storm Climatology and Storm Windfield Methodology

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In this section of the engineering report, the Mapping Partner shall:

- Describe the basic climatological storm data used and the windfield methodology employed.
- Map, tabulate, and discuss in terms of local surge impact the storm paths used in the analysis.
- Tabulate and describe in written form the storm parameters (including central pressure deficit, radius to maximum wind, forward speed, shoreline crossing point, and shoreline crossing angle) used in the analysis.
- Identify sources of the basic data used to develop the storm climatology and the method used to sort the data and compare them with the National Weather Service (NWS) *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States (NWS 38)*.
- Describe the technique employed to determine the spatial/temporal distribution of storm occurrences (i.e., storms/nautical mile/year), derivation and discretization of storm intensity parameters, and exceedence probability distributions.
- Provide graphical presentation of the results, including an overlay with orientation of coast to storm path/direction.
- Provide a discussion of storm parameter independence and any unique storm model treatments.

- Give the exact equations used to parameterize the model windfield along with any unique values of all the appropriate coefficients and constants used. The windfield used in the analysis is a key component in the determination of the storm surge elevation.

- Include a diagram of the windfield model that gives the surface velocity structure as it changes radially outward from the storm center.

- Provide a comparative graph depiction of measured windfield(s) and modeled windfield, if available.

- Describe the method by which winds are reduced as the storm approaches land and moves inland in detail.

- Report the constants used in windspeed reduction.

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### D.1.2.4 Hydrodynamic Storm Surge Model

This section of the engineering report is to address the hydrodynamic storm surge model employed in performing the coastal study. The model used to calculate the surge elevation has been described in detail in various FEMA documents and need only be cited by reference. In this section of the engineering report, the Mapping Partner shall:

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- Report the unique model characteristics used for the study, including a discussion of the specific grid system and sub-grid systems employed, the grid used for bottom topography and shoreline, small-scale features such as harbors and barrier islands, and the location and conditions applied for the open boundaries to the grid.

- Describe and document the adjustment to land features to account for erosion.

- Describe and document the method used to determine average ground elevations and water depths within the cells of the grid system. This discussion should be augmented by diagrams that show the grid systems as computer listings of the grid data used in the actual model calculations.

- Describe the method used to relate windspeed and surface drag coefficient is to be described.

- Discuss the Manning's "n" values used in the calculation of bottom and overland friction and provide values in tabular form. This information will include a discussion of any sensitivity tests used to estimate these values in nearshore water. Nearshore bottom and overland friction is an important part of the overall analysis and, therefore, shall be described with care and sufficient detail.

- Provide a graphical depiction of the model cells and grid system as an overlay to the bathymetric charts and topographic maps covering the study area, annotated with the individual cell inputs for the grid system.

- Discuss the method by which barriers, inlets, and rivers have been treated.
- Explain the procedures used to determine inland flooding, including parameterization of local features and selection of the friction factors used for the terrain.

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### D.1.2.5 Calibration and Verification of Hydrodynamic Storm Surge Model

In this section of the engineering report, the Mapping Partner shall document the calibration and verification of the hydrodynamic surge model. Once the hydrodynamic storm surge model and grid have been set up, calibration and verification are performed. Calibration is done to determine the adjustable "tuning parameters" (e.g., Manning's "n", barrier overflow coefficients) and to validate the chosen grid schematization. Verification is used to validate the model and grid for situations other than the case used to calibrate the model. Sensitivity runs are used to make sure that small changes in the chosen grid and "tuning parameters," will not give rise to unacceptable large changes in the computed flood and tide levels. Calibration and verification computer runs compare computed results with observed water levels. Sensitivity runs compare computed results with other computed results.

When observed (or model simulation) data are employed to calibrate (or compare) hydrodynamic storm surge model results with other available studies, the Mapping Partner shall give a complete description of this calibration procedure (or model comparison), including a listing of measured and simulated tidal data. Calibration (and model comparison) is an important aspect of the model analysis; therefore, the Mapping Partner shall described these activities with sufficient detail and care to allow an independent reviewer to understand the exact procedures employed and the local historical records employed.

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### D.1.2.6 Statistical (Joint Probability) Methodology

If the joint probability method was used, the Mapping Partner shall summarize, map, and report the values and combinations used for storm parameters, annual storm density, spacing between storms, and the storm tracks used in the analysis in this section of the engineering report. In this section, the Mapping Partner also shall compare the information above with the probabilities reported in *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States (NWS 38)*. Specifically, the Mapping Partner shall:

- Note the total number of simulations.
- Summarize tidal elevation data, if used, in sufficient detail to remove any doubt as to the values used in the simulations.
- Describe the method by which the tidal elevation data are convoluted with surge data including tidal constants and tidal records.

- Describe storm occurrence rate or storm density, the definition of the storm region used to define storm density, and storm kinematics and intensity with respect to their use in the joint probability calculation.
- Report and discuss comparisons to long-term gage statistics.
- Describe and report adjustments to account for the combined probability of coastal and riverine flooding for each area where such an approach was taken.

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### D.1.2.7 Unique Computer Programs

Several different computer codes may be used in the wind, hydrodynamic, and joint probability analysis. Several basic computer programs have been listed in numerous FEMA reports. In this section of the engineering report, the Mapping Partner shall list and describe any modifications of these programs and special data inputs used in the study.

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### D.1.2.8 Wave Height, Runup, and/or Erosion Analysis

In this section of the engineering report, the Mapping Partner responsible for performing the coastal analysis shall reference the wave height, runup, and/or erosion analysis methodology used for the study. Specifically, the Mapping Partner shall:

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- Document fully any deviation or expansion of that approach.
- Describe the selection of input data, including a reference to source data and material.
- Document fully all erosion considerations.
- Include one or more transect location maps as appropriate.
- Include computer printout listings for input and output data as an appendix to the report, keyed to the transect location map(s).

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### D.1.2.9 References

In the final section of the engineering report, the Mapping Partner shall provide a complete list of technical references, including computer program references, indicating how to obtain copies of the exact program and the input data sources used in the analysis.

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## D.1.3 Great Lakes Wave Runup Computations and Mapping

Mapping Partners performing coastal studies for communities along the Great Lakes shoreline should use the wave runup analysis guidance in Section D.3. Section D.3 provides a wave runup study flow chart, the detailed study procedure steps, sample computations, and mapping policies. An overview of the coastal study procedures is presented below.

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### D.1.3.1 Wave Runup Calculation Procedures

The guidelines for Great Lakes wave runup calculations have emerged from methodologies recommended by the Detroit District of the U.S. Army Corps of Engineers (USACE) in the study report entitled *Great Lakes Wave Runup Methodology Study*. The figures and tables in Section D.3 have been drawn from various references cited in this USACE study report. Further guidance on the wave runup approach is included in Section D.3. Although this guidance is subject to change based on new information and methodology improvement, it provides the framework and information on the application of the methodologies.

Three types of shorelines are considered: a natural beach profile and two types of armored shoreline profiles (vertical wall and rock revetment). Therefore, three runup methodologies corresponding to the three shoreline types are employed. The flow of tasks begins with site profile data-gathering, tracks through various intermediate steps, such as the 1-percent-annual-chance flood level determination, and the calculation of the deep water and shallow water wave height, and ends with the wave runup determination for each type of shoreline.

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### D.1.3.2 Wave Runup Computation Steps and Sample Calculations

When the site location is identified, the Mapping Partner shall follow the step-by-step study procedures below to determine the maximum wave runup elevations to be used in coastal floodplain boundary delineations.

- Step 1. Profile Data Gathering
- Step 2. 1-percent-annual-chance Flood Level Determination
- Step 3. Offshore (Deep Water) Wave Height Determination
- Step 4. Nearshore (Shallow Water) $H_{mo}$, $H_s$, and $T_p$ Computation
- Step 5. Wave Runup Computation
- Step 6. Determination of Maximum Wave Runup Elevation

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#### D.1.3.3 Delineation and Mapping Policy

Six general policies and 12 specific-case mapping policies accompanied with illustration diagrams may be used in the coastal FIS map delineation for Great Lakes coastal communities. (See Section D.3 for detailed information.) Mapping Partners shall apply the general policies to all cases and the specific-case policy to a certain situation. Three types of shoreline profiles are typical in the Great Lakes region and are used to classify the cases:

- Beach profile with a natural dune system;
- Beach profile with a bluff system; and
- Beach profile with coastal structures.

For each type of shoreline profile, the Mapping Partner shall consider four separate cases, depending on the computed wave height profile, wave runup height, 1-percent-annual-chance stillwater level, and the predicted post-storm erosion profile. For other special cases that cannot be covered by the above policies, the Mapping Partner shall consult with the RPO.

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### D.1.4 Intermediate Data Submission for Coastal Flood Studies

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Coastal analyses involving storm surge modeling are highly specialized and complex and require a highly specialized review process. Experience has shown that attempting to make changes or corrections to coastal storm surge and wave height analyses after they have been run and mapped is not practical due to the time, cost, and contractual problems involved. Many questions and problems that arise during the review process could be answered or resolved much more readily if these issues were raised early in the study process. Therefore, FEMA has established intermediate data submission requirements to permit review of the Mapping Partner's progress on model development at appropriate milestones. The Mapping Partner performing the study shall submit the data to the reviewing Mapping Partner, as specified by the RPO, in accordance with the sequence discussed below.

The Mapping Partner will receive review comments within 30 days of the receipt of each data submission. The Mapping Partner performing the study shall establish a work plan so that the interim review does not cause any delay in the submission of the FIS Report draft and the maps reflecting the results of the coastal study.

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#### D.1.4.1 Before Storm-Surge Model Calibration Runs Are Made

The Mapping Partner performing the study shall submit the following to the reviewing Mapping Partner before calibration runs are made:

1. A large-scale map of the coastal area which delineates both the coarse grid basin(s) and fine grid basin(s);

2. A schematic of each basin (coarse grid and fine grid) showing sub-grid channel locations, widths, bed elevations, and proposed Manning's "n" values for each channel;

3. Historical evidence establishing the importance of various coastal flooding mechanisms (e.g., tropical and extratropical storms, rainfall and riverine events);

4. Basic data relating to the study area (e.g., documented storm erosion, available design analyses for shore protection or other coastal projects, historical shoreline changes);

5. Aerial photographs, coastal setback maps, and other maps used to determine more accurate topographic-bathymetric values and land cover features in the study area;

6. Table listing astronomical tide events and historical storms selected for use in model calibration and verification, and a plot showing the observed storm surge elevation against the predicted tide elevations;

7. Plots of exceedence probability vs. parameter value for the meteorological storm parameters that vary in the joint probability analysis, as developed for the study area following *NWS 38*, with documentation to include a tabular presentation of all meteorological storm parameter data used in development of the exceedence probability curves; and

8. Table showing storm parameter values and assigned probabilities.

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### D.1.4.2 Before Operational Storm Surge Runs Are Made

The Mapping Partner performing the study shall submit the following to the reviewing Mapping Partner before operational storm surge runs are made:

1. A map of each basin (coarse grid and fine grid) showing water depths, ground elevations, and Manning's "n" values for each grid cell;

2. A map of each basin (coarse grid and fine grid) showing barrier locations, barrier heights, barrier widths, barrier Manning's "n" values, location of inlets cutting through barriers, inlet widths, inlet bed elevations, inlet Manning's "n" values and inlet entrance and loss coefficients;

3. A computer printout listing of the water depth, ground elevations, Manning's "n" values, barrier and inlet input, and the sub-grid channel input, and any other input data used in the calibration and verification runs and that will be used in the production runs;

4. Description of sensitivity runs used to optimize model parameters for the study area, for example, in final choices of Manning's "n" values;

5. Tide and storm calibration results (including extreme water elevations and time histories) showing computed results and a comparison of these with observations where such observations are available;

6. Grid overlay and work maps used in storm surge analyses for all fine and open-coast grid basins; and

7. Written documentation, including justification, of any modifications made to the standard FEMA storm surge methodology and a listing of the computer source code annotated where the modifications were made.

The work maps listed in No. 6 above should generally be the 7.5-minute series U.S. Geological Survey quadrangle maps and the hydrographic charts that were used to gather topographic, bathymetric, roughness, and other input data for the storm surge calculations. The Mapping Partner performing the study shall draw the grid pattern on the maps or use one or more transparent overlays registered to the work map(s) to indicate where the grid cells fall with respect to various map features. The Mapping Partner also shall indicate the location and extent of each wave transect on the overlays or work maps.

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### D.1.4.3 Before Operational Wave Elevation Determination Are Made

The Mapping Partner performing the study shall submit the following to the reviewing Mapping Partner before operational wave elevation determinations are made:

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1. Documentation of conclusions on the interaction between storm surge and astronomical tide;

2. Output of PROBS program for all open coast and fine grid basins;

3. Grid showing 10-, 2-, 1-, and 0.2-percent-annual-chance SWFLs for each open coast and fine grid basin; and

4. Location map of proposed transects to be used in the wave elevation determination analyses.

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### D.1.4.4 Before Wave Elevation Determinations Are Mapped

The Mapping Partner performing the study shall submit a copy of all wave height and wave runup transect computations, and all modeling assumptions to the reviewing Mapping Partner before wave elevations and resulting BFEs are mapped.

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## D.2 Wave Elevation Determination and V Zone Mapping: Gulf of Mexico and Atlantic Ocean

The mapping of V Zones under the NFIP began in the early 1970s. The objective was to identify hazardous coastal areas in a manner consistent with the original regulatory definition of coastal high hazard areas as an "area subject to high velocity waters, including but not limited to hurricane wave wash." The initial technical guidance for identifying V Zones was provided in a June 1973 report by the USACE, Galveston District entitled *General Guidelines for Identifying Coastal High Hazard Zone, Flood Insurance Study - Texas Gulf Coast Case Study*, prepared by the U.S. Army Corps of Engineers (USACE), Galveston District (1973). The USACE report identified a breaking wave height of 3 feet as critical in terms of causing significant structural damage and illustrated procedures for mapping the limit of this 3-foot wave (V Zone) in two distinct situations along the Texas coast: undeveloped areas and highly developed areas.

In June 1975, the USACE issued a follow-up report entitled *Guidelines for Identifying Coastal High Hazard Zones* which maintained the basic recommendations contained in the 1973 report for identifying V Zones in undeveloped and developed areas; however, the 1975 report also included guidance for determining effective fetch lengths, a technical discussion justifying the 3-foot wave height criterion for V Zones, an abbreviated procedure for V Zone mapping in undeveloped areas, an expanded discussion of V Zone mapping in developed areas, and historical accounts of several severe storms that have impacted developed areas along the Atlantic and Gulf coasts.

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Between 1975 and 1980, the Federal Government (U.S. Department of Housing and Urban Development until 1978 and FEMA thereafter) published FIRMs with V Zones for approximately 270 communities along the Atlantic and Gulf coasts using the USACE guidance for V Zone mapping. During this period, the procedures for determining and delineating V Zones in developed areas differed among studies. At that time, the regulatory BFEs, for both insurance and construction purposes, were the 1-percent-annual-chance stillwater elevations (SWELs), which consisted of the astronomical tide and storm surge caused by low atmospheric pressure and high winds. Although V Zones were identified, the increase in water-surface elevation due to wave action was not included. The Federal Government recognized that this practice did not accurately represent the flooding hazard along the open coast, but an adequate method for estimating the effects of wave action, applicable to most coastal communities, was not readily available at the time.

In 1976, the National Academy of Sciences (NAS) was asked to provide recommendations about how calculations of wave height and runup should be incorporated in FISs for Atlantic and Gulf coast communities to provide an estimate of the extent and height of stormwater inundation having specified recurrence intervals. The NAS concluded that the prediction of wave heights should be included in FISs for coastal communities and provided a methodology for the open coast and shores of embayments and estuaries on the Atlantic and Gulf coasts. The 1977 report documenting the NAS findings, *Methodology for Calculating Wave Action Effects Associated with Storm Surges* included means for taking into account varying fetch lengths, barriers to wave transmission, and regeneration of waves likely to occur over flooded land areas. NAS did not

address the extent and elevation of wave runup, amount of barrier overtopping, and coastal erosion.

In 1979, FEMA adopted the NAS methodology. In 1980, FEMA issued *Users Manual for Wave Height Analysis*, which was subsequently revised in February 1981. FEMA also introduced a computer program, Wave Height Analyses for Flood Insurance Studies (WHAFIS), in 1980. With WHAFIS, FEMA initiated a large effort to incorporate the effects of wave action on the FIRMs for communities along the Atlantic and Gulf coasts.

Along the New England coast with its very steep shore, the NAS methodology proved to be insufficient. Structures that were shown as being outside of the SFHA on effective FIRMs experienced considerable wave damage from storms, most notably the northeaster of February 1978, a near 1-percent-annual-chance flood event. The need to account for the effects of wave runup was recognized. In 1981 FEMA approved a methodology that determined the height of wave runup landward of the stillwater line. Stone & Webster Engineering Corporation developed the methodology in November 1981. In 1987, FEMA modified its computer model for runup elevations slightly to increase the convenience of preparing input conditions. In 1990, FEMA modified the model again to improve computational procedures and application instructions to conform to the best available guidance on wave runup (Dewberry & Davis, 1990).

Two additions were made to the NAS methodology in 1984 to account for coastal situations involving either marsh grass or muddy bottoms. The NAS methodology did not account for flexible vegetation; in particular, marsh plants. Experts surmised that the motion of submerged marsh plants absorbed wave energy, reducing wave heights. In 1984, a FEMA task force examined this phenomenon in detail and developed a methodology that adjusted the wave height to reflect energy changes resulting from the flexure of various types of marsh plants and the wind, water, and plant interaction (FEMA, 1984). FEMA incorporated the new methodology into WHAFIS.

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The muddy bottom situation occurs only at the Mississippi Delta in the United States. The Mississippi River has deposited millions of tons of fine sediments into the Gulf of Mexico to form a soft mud bottom in contrast to the typical sand bottom of most coastal areas. This plastic, viscous bottom deforms under the action of surface waves. This wave-like reaction of the bottom absorbs energy from the surface waves, thus reducing the surface waves. A methodology was developed for FEMA to calculate the wave energy losses due to muddy bottoms (Suhayda, 1984). Waves in the offshore areas are tracked over the mud bottom, resulting in lower incident wave heights at the shoreline. This is a phenomenon unique to the Mississippi Delta, and FEMA has not incorporated the methodology into WHAFIS.

In 1988, FEMA upgraded WHAFIS to incorporate revised wave forecasting methodologies described in the 1984 Edition of the USACE *Shore Protection Manual* (USACE, 1984) and to compute an appropriately gradual increase or decrease of SWELs between two given values (FEMA, September 1988).

In the performance of wave height analyses and the preparation of FISs, erosion considerations were left to the judgment of FEMA contractors. Coastal erosion was to be considered a hazard

when there was historical evidence of erosion from previous storms, but prior to 1986, objective procedures for treating erosion were not available. Consequently, some shorefront dunes were designated as stable barriers to flooding and some were not. In 1986, FEMA initiated studies aimed at providing improved erosion assessments in FISs for coastal communities.

In response to criticisms indicating a significant underestimation of the extent of Coastal High Hazard Areas, FEMA undertook an investigation to reevaluate V Zone identification and mapping procedures. The resulting report, entitled *Assessment of Current Procedures Used for the Identification of Coastal High Hazard Areas (V Zones)* presented a number of recommendations to allow for more realistic delineation of V Zones and to better meet the objectives of the NFIP for actuarial soundness and prudent floodplain development (FEMA, 1986). One recommendation was for full consideration of storm-induced erosion and wave runup in determining BFEs and mapping V Zones. As part of its investigation, FEMA performed a study of historical cases of notable dune erosion. In this quantitative analysis, field data for 30 events (later increased to 38 events) yielded a relationship of erosion volume to storm intensity as measured by flood recurrence interval. For the 1-percent-annual-chance storm, FEMA determined that, to prevent dune breaching or removal, an average cross-sectional area of 540 square feet is required above the SWEL and seaward of the dune crest. That standard for dune cross section has a central role in erosion assessment procedures.

The USACE Coastal Engineering Research Center (CERC) performed a study of the available quantitative erosion models for FEMA (Birkemeier, Kraus, Scheffner, & Knowles, 1987). USACE determined that only empirically based models produce reasonable results with a minimum of effort and input data, that each available model for simple dune retreat has certain limitations, and that dune overwash processes are poorly documented and unquantified. After further investigations, FEMA decided to employ a set of extremely simplified procedures for objective erosion assessment (FEMA, November 1988). These procedures have a direct basis in documented effects due to extreme storms and are judged appropriate for treating dune erosion in FISs for coastal communities.

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As the official basis for treating flood hazards near coastal sand dunes, FEMA published new rules and definitions in the *Federal Register* that became effective on October 1, 1988. FEMA included the following revised definition in Section 59.1 of the NFIP regulations:

> *Coastal high hazard area* means an area of special flood hazard extending from offshore to the inland limit of a primary frontal dune along an open coast and any other area subject to high velocity wave action from storms or seismic sources.

FEMA also added a clarification of this matter, a definition of primary frontal sand dune, in Section 59.1:

> *Primary frontal dune* means a continuous or nearly continuous mound or ridge of sand with relatively steep seaward and landward slopes immediately landward and adjacent to the beach and subject to erosion and overtopping from high tides and waves during major coastal storms. The inland limit of the primary frontal dune occurs at the point where there is a distinct change from a relatively steep slope to a relatively mild slope.

FEMA also included a new section in Part 65 of the NFIP regulations, identifying a cross-sectional area of 540 square feet as the basic criterion to be used in evaluating whether a primary frontal dune will act as an effective barrier during the 1-percent-annual-chance flood. Another consideration is the documented historical performance of coastal sand dunes in extreme local storms.

In 1989, USACE completed a review for the NFIP regarding coastal structures as protection against the 1-percent-annual-chance flood (Walton, Ahrens, Truitt, & Dean, 1989). Predictions of wave forces, wave overtopping, and wave transmission for commonly occurring structures were among technical topics addressed in the USACE report. The guidelines in this Appendix incorporate procedural criteria recommended by the USACE for evaluating structural stability.

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## D.2.1 Organization and Overview

Figure D-1 presents a flowchart of appropriate procedures for defining coastal hazards of the 1-percent-annual-chance flood. Fundamental aspects of the 1-percent-annual-chance flood are addressed in the following sequence:

1. SWEL,
2. Accompanying wave conditions,
3. Stability of coastal structures,
4. Storm-induced erosion,
5. Wave runup and overtopping, and
6. Overland wave heights.

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Determination of SWELs usually involves detailed statistical analyses, but added effects due to surface wave action are treated by simplified deterministic methodologies. This strategy avoids any potential complications due to conditional probabilities for simultaneous flooding effects. The sequence for treating these effects is entirely consistent in principle; for example, added wave effects are not resolved within the equations commonly used to simulate coastal storm surges and establish SWEL for the 1-percentannual-chance flood.

The order indicated in Figure D-1 for activities, assessments, and analyses also outlines the organization of topics treated in these guidelines. Subsection D.2.2 provides general data requirements for conducting a coastal study, including that data needed as input to computer models. Subsection D.2.3 discusses requisite evaluation of coastal structures potentially providing wave and/or flood protection. Subsection D.2.4 considers the erosion assessment needed to project the configuration of the shore profile during the 1-percent-annual-chance flood. Subsection D.2.5 treats wave runup, wave setup, and overtopping occurring at shore barriers in flood conditions. Subsection D.2.6 addresses the analysis of nearshore wave heights

and wave crest elevations relevant to a study. Each of these sections provides guidance on the models and procedures for treating individual transects at a study site.

FEMA has established specific models and procedures for the evaluation of shore structures, erosion, wave runup, and wave heights in the determination of coastal flood hazards. For many coastal areas, all four topics must be considered for an adequate treatment; for other coastal areas, application of only one or two of the FEMA methodologies may be required to produce reasonable results. Table D-1 lists some typical shoreline types and the models that should be used for them.

**Table D-1. Model Selection for Typical Shorelines**

| TYPE OF SHORELINE | MODELS TO BE APPLIED | | |
|---|---|---|---|
| | EROSION | RUNUP | WHAFIS |
| Rocky bluffs | | x | x |
| Sandy bluffs, little beach | x | x | x |
| Sandy beach, small dunes | x | | x |
| Sandy beach, large dunes | x | x | x |
| Open wetlands | | | x |
| Protected by rigid structure | | x | x |

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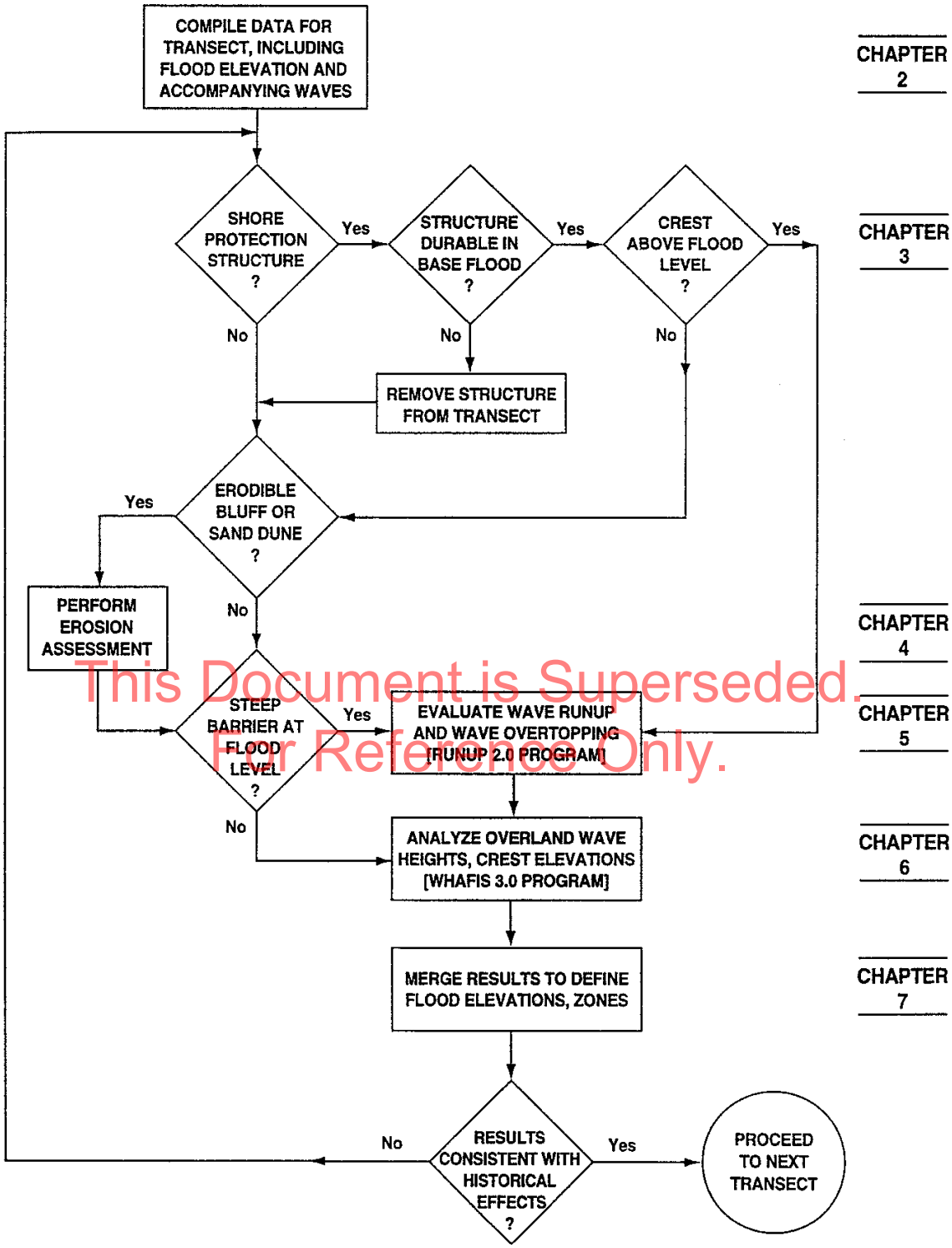


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**Figure D-1. Procedural Flowchart for Defining Coastal Flood Hazards**

The remaining material in these guidelines adopts a more comprehensive view toward completion of an FIS. Subsection D.2.7 addresses the integration of basic results into a coherent map for flood elevations and hazard zones. Subsection D.2.8 defines required documentation of the process, decisions, and data used in determining coastal flood hazards for a community. For consistency with the NFIP and compatibility with FISs, these guidelines use standard English units for all variables.

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## D.2.2 Data Requirements for Coastal Flood Hazard Analyses

To conduct a study for a coastal community, the Mapping Partner performing the study shall first collect the wide variety of quantitative data and other site information required in ensuing analyses. This subsection describes how coastal flood elevations and boundaries are determined, including an outline for the storm expected to cause the 1-percent-annual-chance flood, and characteristics of nearshore seabed through upland regions. Some data are directly input to computer models of flood effects, and other data are used to interpret and integrate the calculated results.

Each computer model of a separate flood effect is executed along transects, which are cross sections taken perpendicular to the mean shoreline to represent a segment of coast with similar characteristics. Thus, collected data are compiled primarily for transects, in turn situated on work maps at the final scale of the FIRM. Work maps are used both to locate and develop the transects, and to interpolate and delineate the flood zones and elevations.

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Aside from needed quantitative information, the Mapping Partner shall collect descriptions of previous flooding and the community in general to aid in the evaluation of flood hazards and for inclusion in the FIS Report. The Mapping Partner shall start data collection at the community level and proceed with county, state, and Federal agencies. The Mapping Partner also shall contact private firms specializing in topographic mapping and/or aerial photography, following up suggestions provided by government agencies.

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### D.2.2.1 Stillwater Elevations

The Mapping Partner shall determine the SWELs in a rational, defensible manner and shall not include contributions from wave action either as a result of the mathematics of the predictive model or of the data used to calibrate the model. Only the 1-percent-annual-chance SWEL is required for the coastal analyses, although 10-, 2-, and 0.2-percent-annual-chance elevations are provided in the FIS Report, and the 0.2-percent-annual-chance floodplain boundary is mapped on the FIRM.

SWELs may be defined by statistical analysis of available tide gage records or by calculation using a storm surge computer model. A minimum of 20 years of recorded tide data is needed if the SWEL is to be based on tide gage records alone. Measured tide levels are preferred over

synthetic models provided they have a significant period of continuous record over 20 years and can accurately represent the geographic area of the study. FEMA has available a self-contained hurricane storm surge model that can provide flood elevations (FEMA, August 1988) and a synthetic northeaster model that simulates the wind and pressure fields of an extratropical storm for input to a storm surge computer model (Stone & Webster Engineering Corporation, 1978). The Mapping Partner shall use these computer models for complex shorelines where gage records are limited, nonexistent, or non-representative, and usually indicate appreciable variations in flood elevations within a community. FEMA also has specified procedure and documentation for coastal flood studies using a storm surge model, as presented previously in Subsections D.2.2, D.2.3 and D.2.4. Of particular importance here, the surge model study can provide winds and water levels over time likely with the 1-percent-annual-chance flood.

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### D.2.2.2 Selected Transects

The Mapping Partner shall locate transects with careful consideration given to the physical and cultural characteristics of the land so that they will closely represent conditions in their locality. The transects are to be placed closer together in areas of complex topography, dense development, unique flooding, and where computed wave heights and runup may be expected to vary significantly. Wider spacing may be appropriate in areas having more uniform characteristics. For example, a long stretch of undeveloped shoreline with a continuous dune or bluff having a fairly constant height and shape, and similar landward features may require a transect only every 1 to 2 miles, whereas a developed area with various building densities, protective structures, and vegetation cover may require a transect every 1,000 feet.

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Good judgment exercised in placing required transects will avoid excessive interpolation of elevations between transects, while also avoiding unnecessary study effort. In areas where runup may be significant, the proper location of transects will be governed by variations in shore slope or gradient. On coasts with sand dunes, the Mapping Partner shall site transects according to major variations in the dune geometry and the upland characteristics. In other areas where dissipation of wave heights may be most significant to the computation of flood hazards, the Mapping Partner shall base transect location on variations in land cover: buildings, vegetation, and other factors. Generally speaking, the Mapping Partner shall site a separate transect at each flood protection structure. However, if areas with similar characteristics are scattered throughout a community and have the same SWEL, the Mapping Partner may apply the results from one transect at various locations within this common area. This should be done only after careful consideration is given to topographic and cultural features to assure the accurate representation of the coastal hazards.

The Mapping Partner shall locate the transects on the work map with the input data compiled on a separate sheet for each transect. The data for the transect are not taken directly along the line on the work map; they are taken from the area, or length of shoreline, to be represented by the transect so that the input data depict average characteristics of the area. Because of this, the Mapping Partner may find it is useful to divide the work map into transect areas for data compilation.

### D.2.2.3 Topography

The topographic data must have a contour interval no greater than 5 feet or 1.5 meters. FEMA does not require more detailed information such as spot elevations or a smaller contour interval, although they can be useful in the definition of the dune or bluff profile and in the delineation of floodplain boundaries. The topographic data, usually in the form of maps, must be recent and reflect current conditions or, at a minimum, conditions at a clearly defined time. Transects need not be specially surveyed unless available topographic data are unsuitable or incomplete. The Mapping Partner shall examine the topographic data to confirm that the information to be used in the analysis and mapping represents the actual planimetric features that might affect identification of the coastal hazards.

If possible, the Mapping Partner shall field-check shore topography to note any changes due to construction, erosion, coastal engineering, and other factors. The Mapping Partner shall document any significant changes with location descriptions, drawings, and/or photographs. The community, county, and state are usually the best sources for topographic data. The Mapping Partner shall examine USGS 7.5-minute series topographic maps. The USGS maps may have a 5-foot contour interval; if not, they are still often useful as reference or base maps.

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### D.2.2.4 Land Cover

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The land-cover data include information on buildings and vegetation. Stereoscopic aerial photographs can provide the required data on structures and some of the data on vegetation. The Mapping Partner shall ensure that aerial photographs are not more than 5 years old unless they can be updated by surveys. Local, county, or state agencies may have the coastline photographed on a periodic basis, and may provide photographs or permission to obtain them from their source.

Aerial photographs can provide the required data on tree- and bush-type vegetation. However, although they are useful in identifying areas of grass-like vegetation, they cannot identify specific types. National Wetland Inventory maps from the U.S. Fish and Wildlife Service and color infrared aerial photographs can provide some more specific data required for marsh plants. Ground-level photographs are also useful in providing information on plants. State offices of coastal zone management, park and wildlife management, and/or natural resources should be able to provide information. The Mapping Partner also may contact local universities with coastal studies and/or Sea Grant programs. The Mapping Partner may conduct field surveys in lieu of the above sources, but are more cost effective when used only to supplement or verify data obtained from these sources.

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### D.2.2.5 Bathymetry

The Mapping Partner may acquire bathymetric data from National Ocean Service nautical charts, although any reliable source may be used. The bathymetry must extend far enough offshore to include the breaker location for the 1-percent-annual-chance flood; although that depth may not be exactly known during the data collection phase, the Mapping Partner may assume that a mean water depth of 40 feet will encompass all typical breaker depths. Bathymetry further offshore also may be useful in interpreting likely differences between nearshore and offshore wave conditions and necessary where offshore waves are more readily specified.

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### D.2.2.6 Storm Meteorology

The 1-percent-annual-chance flood elevations represent a statistical summary and likely do not correspond exactly to any particular storm event. However, the meteorology of storms expected to provide approximate realizations of the 1-percent-annual-chance flood can be useful information in deciding recurrence intervals for historical events and in assessing wave characteristics likely associated with the 1-percent-annual-chance flood. An important distinction of the flood source from Delaware to Maine is whether the 1-percent-annual-chance flood is more likely to be caused by a hurricane or by a Northeaster. The Mapping Partner shall establish this distinction in the course of defining the SWELs, because time history of water levels can be radically different in the two possible cases (see Figure D-2).

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For a Northeaster, commonly a winter storm occurring between October and March, sustained winds seldom reach much above 60 mph, storm surge has relatively modest magnitude, and surge coincidence with spring high tides is usually required to attain the 1-percent-annual-chance SWEL. Extreme storms that occurred with lower tides can indicate wind and wave conditions also likely to accompany the 1-percent-annual-chance flood. Thus, the Mapping Partner can assemble a fair amount of pertinent historical evidence regarding expected meteorological conditions for the 1-percent-annual-chance flood arising from an extratropical storm. The dominant conditions include speed and duration of sustained winds, along with the storm size controlling fetch along which waves may be generated.

Where hurricanes are of primary importance, the 1-percent-annual-chance flood is likely associated with central pressure deficits having exceedance probabilities between 5 and 10 percent (FEMA, August 1988). That description generally corresponds to a major hurricane, where sustained winds exceed 120 mph. Other meteorological characteristics are likely to be fairly typical for the study area and may be determined using the hurricane climatology documented in *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States* (Ho, Su, Hanevich, Smith, & Richards, 1987). That guidance includes localized probabilities for central pressure deficit, radius to maximum winds, and speed and direction of storm motion.

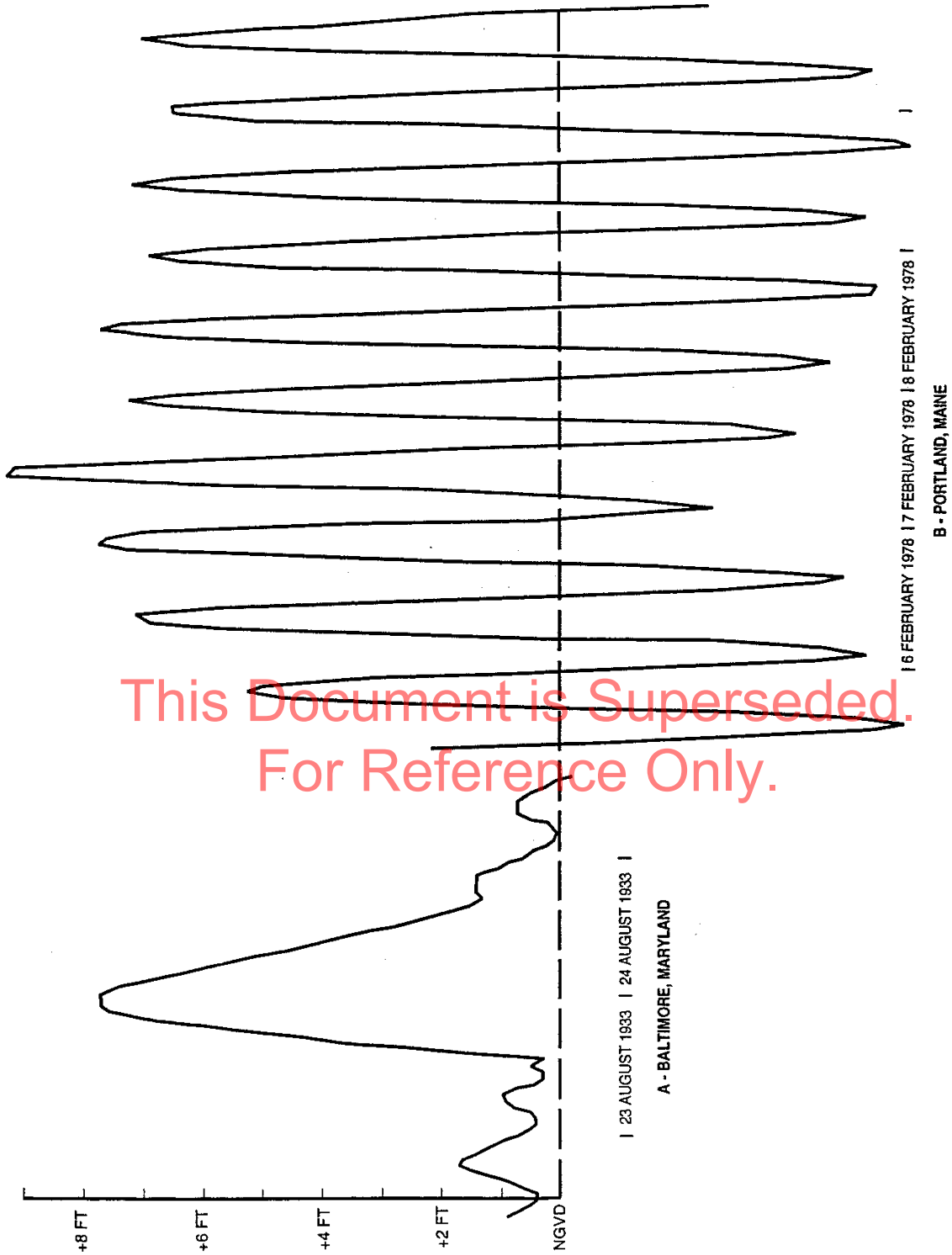


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**Figure D-2. Gage Records of Floods Peaking near the Local 1-Percent-Annual-Chance SWELs, Caused by, A- a Hurricane; and B- an Extratropical Storm**

### D.2.2.7 Storm Wave Characteristics

The basic presumption in conducting coastal wave analyses is that wave direction must have some onshore component, so that wave hazards occur coincidentally with the 1-percent-annual-chance flood. That presumption appears generally appropriate for open coasts and along many mainland shores of large bays, where the 1-percent-annual-chance SWEL must include some contribution from direct storm surge and thus requires an onshore wind component. However, an assumption of onshore waves coincident with a flood may require detailed justification along the shores of connecting channels, in complex embayments, near inlets, and behind protective islands. Once it is confirmed that sizable waves likely travel onshore at a site during the 1-percent-annual-chance flood, the storm wave condition must be defined for assessments of coastal structure stability, sand dune erosion, wave runup and overtopping, and overland elevations of wave crests.

It is important to recognize that somewhat different descriptions of storm waves (Table D-2) can be appropriate in assessing each distinct flooding effect. This depends mainly on the formulation of an applicable empirical or analytical treatment for each effect. In FIS models and analyses, the different wave descriptions include the following:

- Various wave statistics (e.g., mean wave condition for runup elevations, but an extreme or controlling height for overland waves);
- Various dominant parameters (e.g., incident wave height for overtopping computation, but incident wave period for overland crest elevations); and
- Various specification sites (e.g., deep water for estimating runup elevations, but waves actually reaching a structure in shallow water for most stability or overtopping considerations).

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To proceed with general orientation, the Mapping Partner may develop storm wave conditions from actual wave measurements, from wave hindcasts or numerical computations based on historical effects, and from specific calculations based on assumed storm meteorology. Where possible, the Mapping Partner shall pursue two or all three of these possibilities in estimating wave conditions expected to accompany the 1-percent-annual-chance flood at a study site. Using all available information can improve the level of certainty in estimated storm wave characteristics.

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

**Table D-2. Some Commonly Used Specifications of Irregular Storm Waves**

| SYMBOL | NAME | DESCRIPTION |
|---|---|---|
| **Wave Heights** (water depth must be given) | | |
| $H_s$ | Significant | average over highest one-third of waves |
| $H_c$ | Controlling | defined as (1.6 $H_s$) in NAS (1977) |
| $\overline{H}$ | Mean | average over all waves |
| $H_{mo}$ | zero moment | defined by the variance of water surface, and about equal to $H_s$ in deep water |
| **Wave Periods** (basically invariant with water depth) | | |
| $T_s$ | significant | associated with waves at significant height |
| $T_p$ | peak | represents the maximum in energy spectrum |
| $\overline{T}$ | mean | average over all waves |

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

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

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

Major factors in wave generation are windspeed, wind duration, water depth, and fetch length. Fetch length is he over-water distance toward the wind along which waves arise (USACE, 1994). These factors determine flux of momentum and energy from the atmosphere into waves on the water surface. For some cases, fetch length might be estimated as straight-line distance in the wind direction, but the current ACES guidance pertinent to many partially sheltered coastal sites indicates that a more involved analysis of restricted fetches must be performed for water basins of relatively complex geometry. The effective fetch length is derived as a weighted average of over-water distance with angle from the wind direction. With specified geometry for a restricted fetch, the ACES program carries out computations necessary for the desired estimates of representative wave height and wave period (Leenknecht et al., 1992).

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

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### D.2.2.8 Coastal Structures

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The Mapping Partner shall obtain documentation for each coastal structure possibly providing protection from 1-percent-annual-chance flood. That documentation shall include the following:

- Type and basic layout of structure;
- Dominant site particulars,(e.g., local water depth, structure crest elevation, ice climate);
- Construction materials and present integrity;
- Historical record for structure, including construction date, maintenance plan, responsible party, repairs after storm episodes; and.
- Clear indications of effectiveness or ineffectiveness.

The Mapping Partner shall develop much of this information through office activity, including a careful review of aerial photographs. In some cases of major coastal structures, site inspection would be advisable to confirm preliminary judgments.

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#### D.2.2.9 Historical Floods

While not required as input to any of the FEMA coastal models, local information regarding previous storms and flooding can be very valuable in developing accurate assessments of coastal flood hazards and validation of storm surge models. General descriptions of flooding are useful in determining what areas are subject to flooding and in obtaining an understanding of flooding patterns. More specific information, such as the location of buildings flooded and damaged by wave action, can be used to verify the results of the coastal analyses. Detailed information on pre- and post-storm beach or dune profiles is valuable in checking the results of the erosion assessment.

When quantitative data are available on historical flooding effects, the Mapping Partner shall make a special effort to acquire all recorded water elevations and wave conditions for the vicinity. That information can be used in estimating recurrence intervals for SWELs and for wave action in the event, assisting an appropriate comparison to the 1-percent-annual-chance flood.

Local, county, and state agencies are usually good sources of historical data, especially more recent events. It is becoming common practice for these agencies to record significant flooding with photographs, maps, and/or surveys. Some Federal agencies (e.g., the USACE, USGS, and National Research Council) prepare post-storm reports for more severe storms. Local libraries and historical societies may also be able to provide useful data.

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### D.2.3 Evaluation of Coastal Structures

The purpose of the evaluation is to determine whether each individual coastal structure appears properly designed and maintained in order to provide protection from the 1-percent-annual-chance flood. If a particular structure can be expected to be stable through the 1-percent-annual-chance flood, the structure geometry may figure in all ensuing analyses of wave effects accompanying the flood: coastal erosion, runup and overtopping, and wave crest elevations. Otherwise, the coastal structure is considered to be destroyed during the 1-percent-annual-chance flood and removed from the transect representation before proceeding with analyses of wave effects.

*Criteria for Evaluating Coastal Flood-Protection Structures* presents a technical review and recommends procedural criteria for evaluating coastal flood protection structures in regard to the 1-percent-annual-chance flood (Walton, Ahrens, Truitt, & Dean, 1989). The FEMA "Memorandum on Criteria for Evaluating Coastal Flood Protection Structures for National Flood Insurance Program Purposes" includes an account of the evaluation process (FEMA, 1990). FEMA has adopted that memorandum as the basis for NFIP accreditation of new or proposed coastal structures in reducing effective flood hazard areas and elevations. Ideally, these evaluation criteria could be applied to existing coastal structures, but available information about older structures typically is not sufficient to complete the detailed evaluation. Where complete information is not available for an existing structure, the Mapping Partner shall make an

engineering judgment about its likely stability based on a visual inspection of physical conditions and any historical evidence of storm damage and maintenance.

*Criteria for Evaluating Coastal Flood-Protection Structures* addressed coastal flood protection structures and identified the four primary types according to a functional standpoint: gravity seawalls, pile-supported seawalls, anchored bulkheads, and dikes or levees. The report recommends as a general policy that "FEMA not consider anchored bulkheads for flood-protection credit because of extensive failures of anchored bulkheads during large storms" (Walton et al., 1989, p. 100).

Flood protection structures can have a significant effect on the flood hazard information shown on a FIRM, perhaps directly justifying the removal of sizable areas from the coastal high hazard area. The focus on flood protection structures in the FEMA memorandum cited above should not divert a recognition that similar considerations are appropriate in crediting the protection provided by structures in categories other than those named in the memorandum, and that such credit can be important. In contrast to flood protection, a breakwater primarily may act to limit wave action and a revetment primarily may control shore erosion, but any stable coastal structure can notably affect results of various hazard analyses for the 1-percent-annual-chance flood, and the Mapping Partner shall take these effects into account. The FEMA memorandum places the responsibility on local interests to certify new structures, but the primary consideration in an FIS must be that the structure evaluation yields a correct judgment based on available evidence. This is necessary for accurate hazard assessments, because a structure might decrease flood effects in one area while increasing erosion and wave hazards at adjacent sites. Of course, the greater the potential effects of a coastal structure, the more detailed should be the evaluation process.

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In areas where buildings conforming to V-Zone construction standards are elevated above the wave crest elevation, the Mapping Partner shall model the piles supporting the structure as obstructions in the wave height analysis. The building itself, being elevated, shall not be modeled as an obstruction to wave propagation.

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## D.2.4 Erosion Assessment

Coastal sand dunes usually extend above the 1-percent-annual-chance SWEL, but such barriers to flooding may not be durable because of massive shorefront erosion occurring during a 1-percent-annual-chance flood. Storm-induced erosion will remove or significantly modify most frontal dunes on U.S. coasts. This is particularly true on barrier islands known historically to be susceptible to storm overwash. Therefore, the Mapping Partner shall assess coastal erosion before determining wave elevations and mapping V Zones for the 1-percent-annual-chance flood.

Available procedures for computing erosion show limited precision in documented hindcasts of recorded erosion quantities and have questionable pertinence to the entire range of erosion effects possible on U.S. coasts. Therefore, a rather schematic treatment of expected erosion quantities and geometries has been developed as an appropriate approach for treating erosion in

FISs. The overall rationale and level of detail in these erosion assessment procedures closely parallel the simple and effective NAS methodology for calculating wave action effects associated with storm surges (NAS, 1977).

The procedures described here are empirically valid for treating dune erosion during the 1-percent-annual-chance flood. These procedures are meant to give schematic estimates of eroded profile geometry suitable for FEMA flood study purposes. The simplified estimates are suitable erosion approximations for extreme storms at sandy sites with typical open-coast wave and flood climate. The erosion assessment procedures that follow are intended for application to natural sites where there are no coastal structures such as breakwaters, groins, or revetments. Scour in front of certified structures can account for eroded sand quantities and an adjustment of the shore profile.

Quantitative considerations here are based on measured sand erosion accompanying extreme floods from hurricanes or extratropical storms on the U.S. Atlantic and Gulf coasts (FEMA, November 1988). For the study site, the Mapping Partner may use storm meteorology along with associated flood and wave characteristics to assess whether such open-coast effects can be typical of anticipated local erosion for the 1-percent-annual-chance flood. Of course, the Mapping Partner shall examine any local historical evidence on storm erosion in deciding applicability of the procedures below.

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### D.2.4.1 Basic Erosion Considerations

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The primary factor controlling the basic type of dune erosion is the pre-storm cross section lying above the 1-percent-annual-chance SWEL (frontal dune reservoir). The Mapping Partner shall determine this area to assess the stability of the dune as a barrier. If the elevated dune cross-sectional area is very large, erosion will result in retreat of the seaward duneface with the dune remnant remaining as a surge and wave barrier. On the other hand, if the dune cross-sectional area is relatively small, erosion will remove the pre-storm dune leaving a low, gently sloping profile. Different treatments for erosion are required for these two distinct situations because no available model of dune erosion suffices for the entire range of coastal situations.

Figure D-3 introduces terminology for two representative dune types. A frontal dune is a ridge or mound of unconsolidated sandy soil, extending continuously alongshore landward of the sand beach. The dune is defined by relatively steep slopes abutting markedly flatter and lower regions on each side. For example, a barrier island dune has inland flats on the landward side, and the beach or back beach berm on the seaward side. The dune toe is a crucial feature and can be located as the junction between gentle slope seaward and a slope of 1:10 or steeper marking the front duneface. The rear shoulder, as shown on the mound-type dune in Figure D-3, is defined by the upper limit of the steep slope on the dune's landward side.

The rear shoulder of mound-type dunes corresponds to the peak of ridge-type dunes. Once erosion reaches those points, the remainder of the dune offers greatly lessened resistance and is highly susceptible to rapid and complete removal during a storm. Figure D-3 shows the location of the "frontal dune reservoir," above 1-percent-annual-chance SWEL and seaward of the dune

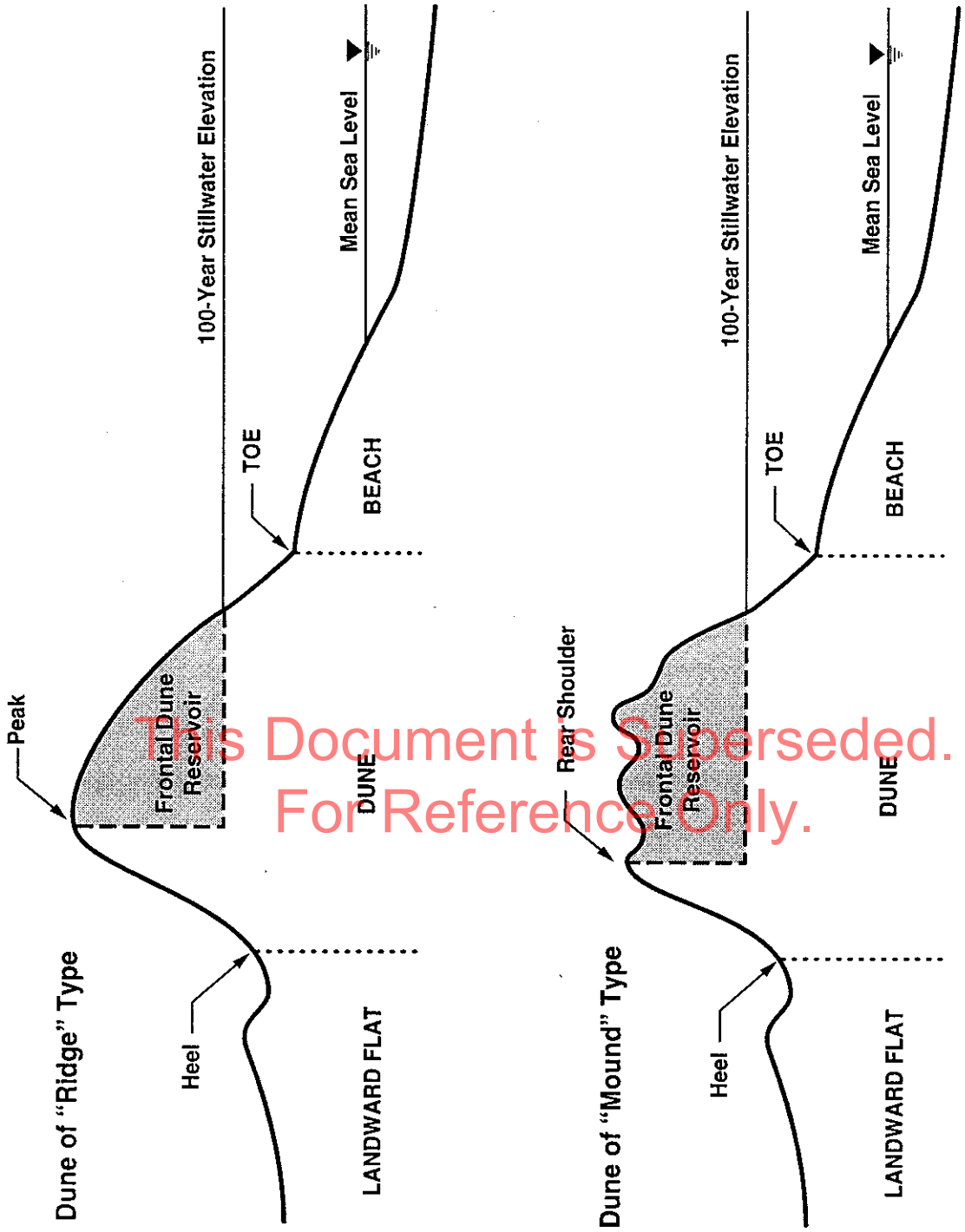


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**Figure D-3. Dune Features and Present Terminology**

peak or rear shoulder. The amount of frontal dune reservoir determines dune integrity under storm-induced erosion.

To prevent dune removal during the 1-percent-annual-chance storm, the frontal dune reservoir must typically have a cross-sectional area of at least 540 square feet (or 20 cubic yards volume per foot along the shore) (FEMA, September 1986; FEMA, November 1988). For more massive dunes, erosion will result in duneface retreat, with an escarpment formed on the seaward side of the remaining dune. To compute the eroded profile in such cases, FEMA has adopted a simplified version of the dune retreat model developed by Delft Hydraulics Laboratory of the Netherlands. This treatment is also appropriate in cases with sandy bluffs or headlands extending above the 1-percent-annual-chance SWEL. The simplified treatment of duneface retreat is described in Subsection D.2.4.3.

If a dune has a frontal dune reservoir less than 540 square feet, storm-induced erosion can be expected to obliterate the existing dune with sand transported both landward and seaward. The Mapping Partner shall estimate the eroded profile using procedures presented in Subsection D.2.4.2. Those procedures provide a realistic eroded profile across the original dune, but do not determine detailed sand redistribution by dune erosion, overwash, and breaching.

Quantitative treatment of overwash processes is not feasible at present (Birkemeier, Kraus, Scheffner, & Knowles, June 1987), so the frontal dune is simply removed.

The initial decision in treating erosion as duneface retreat or as dune removal is based entirely on the size of the frontal dune reservoir. For coastal profiles more complicated than those in Figure D-3, the Mapping Partner shall use judgment to separate the sand reservoir expected to be effective in resisting dune removal from the landward portion of the pre-storm dune. The Mapping Partner shall complete the erosion assessment for the shoreline conditions representative of either the summertime shore profile for hurricane effects or the wintertime shore profile for Northeaster storm effects, whichever is the appropriate and predominant source of coastal flooding that has been selected for use in the coastal hydraulic analyses and erosion assessment.

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Figure D-4 presents a complete flowchart of necessary erosion considerations, outlining the major alternatives of duneface retreat and dune removal. Figure D-5 provides schematic sketches of the different geometries of dune erosion arising in coastal flood hazard assessments.

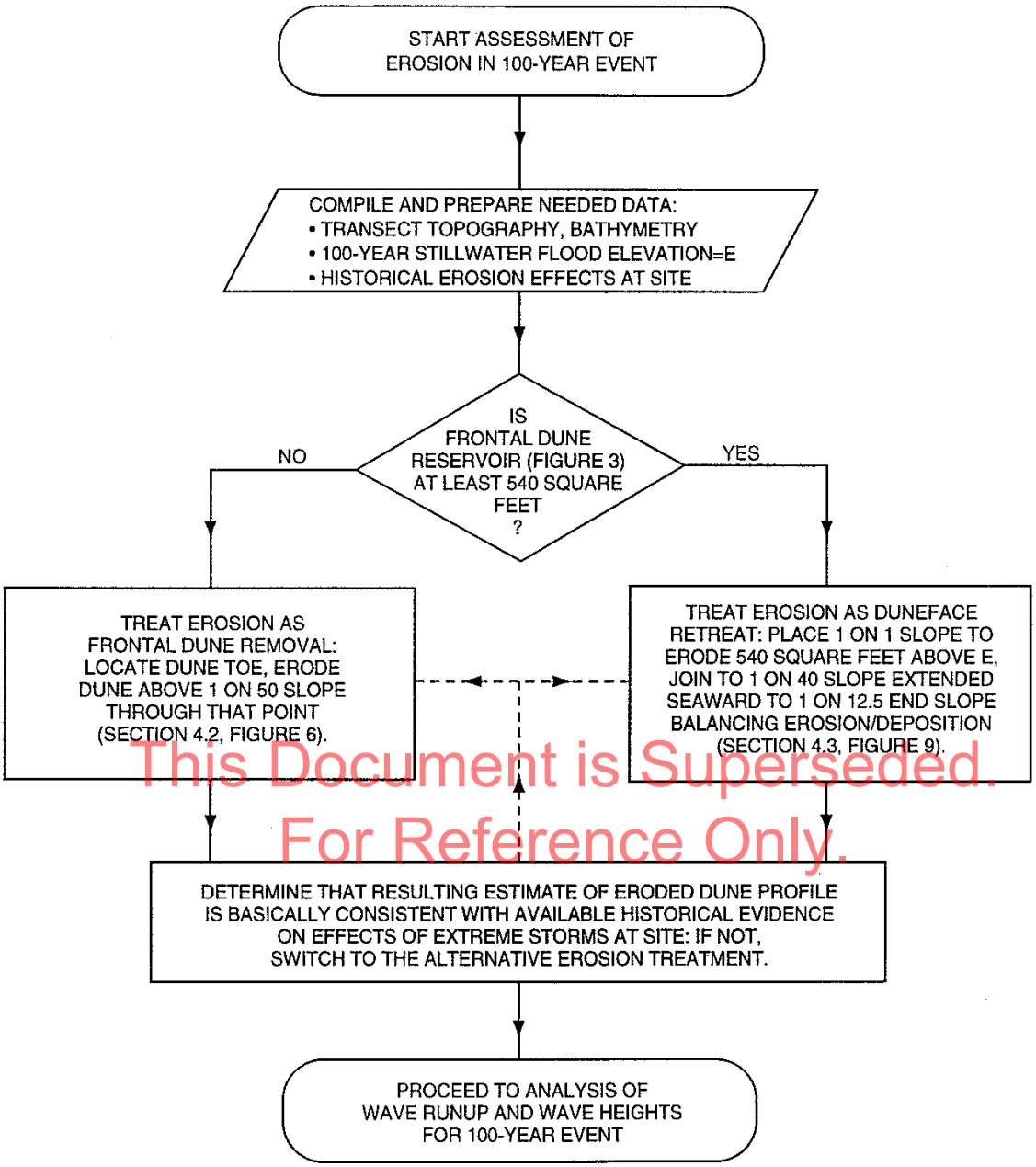


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**Figure D-4. Flowchart of Erosion Assessment for a Coastal Flood Insurance Study**

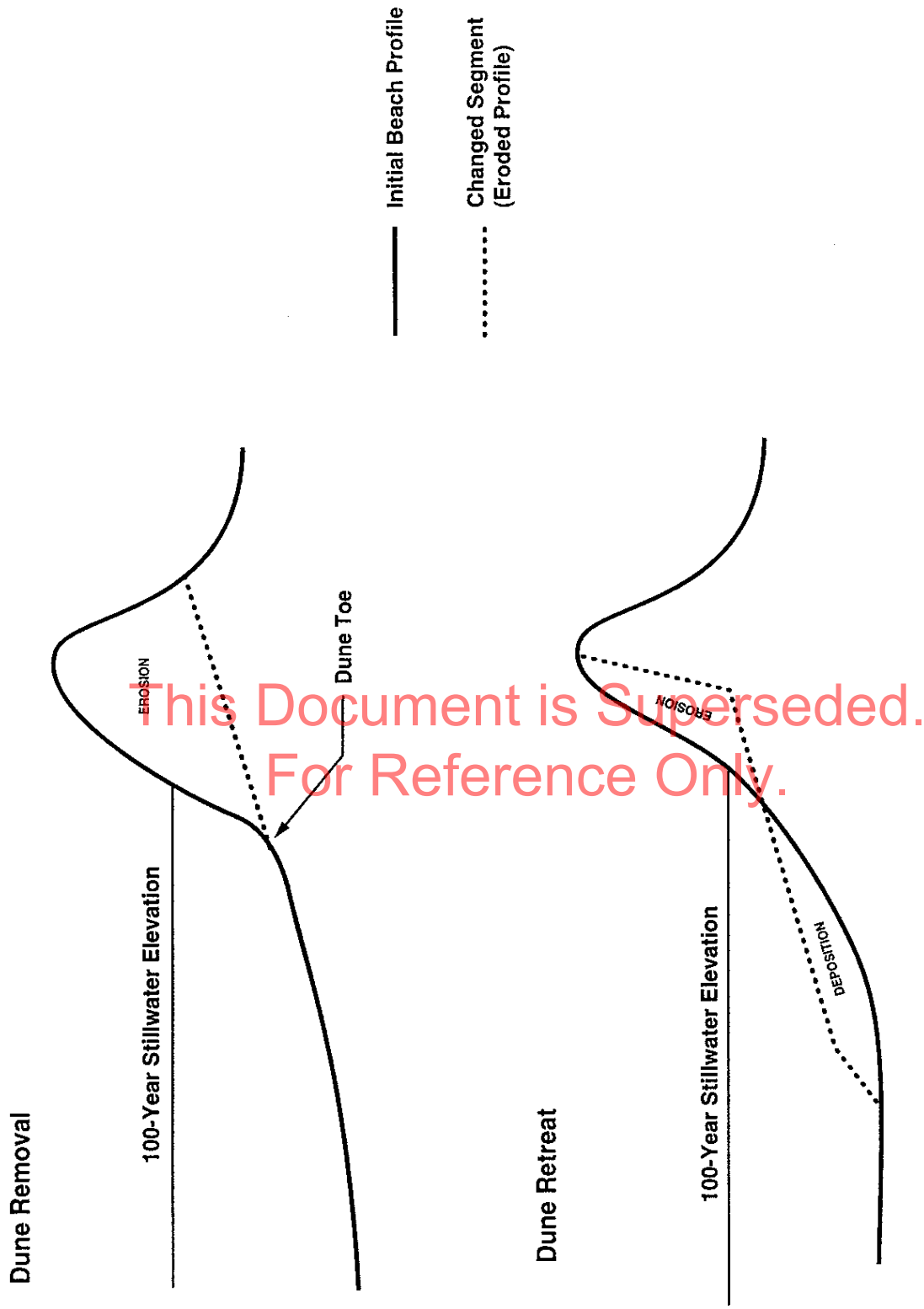


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**Figure D-5. Schematic Cases of Eroded Dune Geometries with Planar Slopes**

One additional factor complicating erosion assessment is the dissipative effect of wide sand beaches that shelter dunes from the full storm impact and retard retreat or removal. If the existing slope between mean level and the 1-percent-annual-chance SWEL is 1:50 or gentler, overestimation of erosion is possible during the 1-percent-annual-chance flood; therefore, the Mapping Partner shall examine this carefully. This effect and other variables, such as sand size, dune vegetation, and actual storm characteristics at a specific site, make thorough comparison of estimated erosion to documented historical effects in extreme storms necessary.

[February 2002]

### D.2.4.2 Treatment of Dune Removal

Determining the dune reservoir requires assessing the profile area located above the 1-percent-annual-chance flood level and seaward of the crest of the primary dune (see Figure D-3). Where the frontal dune reservoir is less than 540 square feet, construction of the eroded profile is extremely simple: dune removal is effected by means of a seaward-dipping slope of 1:50 running through the dune toe. The eroded profile is taken to be that slope across the pre-storm dune, simply spliced onto the flanking segments of a given transect. This gives a gentle ramp across the extended storm surf zone adequate as a first approximation to the profile existing at the storm's peak. This treatment simply removes the major vertical projection of the frontal dune from the transect.

Construction of an eroded profile focuses on the usually distinct feature termed the dune toe. The dune toe is taken to be the junction between the relatively steep slope of the front duneface and the notably flatter seaward region of the beach or the backbeach berm (including any minor foredunes). If a clear slope break is not apparent on a given coastal transect, its location should be taken at the typical elevation of definite dune toes on nearby transects within the study region. The alternative is to set the dune toe at the 10-percent-annual-chance SWEL in the vicinity: that appears to be a generally adequate approximation along the Atlantic and Gulf coasts. In every case, the dune toe must be taken at an elevation above that of any beach berms on local shores.

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Figures D-6, D-7, and D-8 display examples of this treatment for a removed dune. These simple constructions give appropriate estimates for the limits of high ground removed during the 1-percent-annual-chance flood, but cannot provide accurate representations of eroded profiles because of the complicated processes of dune failure. One example of overly simplified results is that deeper scour appears to occur where the frontal dune reservoir is relatively large.

The present viewpoint is consistent with this basic description of storm-induced erosion: greater erosion occurs where the pre-storm barrier provides more resistance; that is, has a relatively large cross section but still is removed during the 1-percent-annual-chance flood. Net shore erosion appears to be maximum for situations where the dune barrier apparently just failed, and the eroded cross section can be much greater than in cases of duneface retreat. A slight opening to landward flow as an eroded dune becomes an overwash channel can result in much deeper scour than in cases of duneface retreat, where most shore erosion is above the SWEL as duneface sand is continuously deposited in shallow water during the storm.

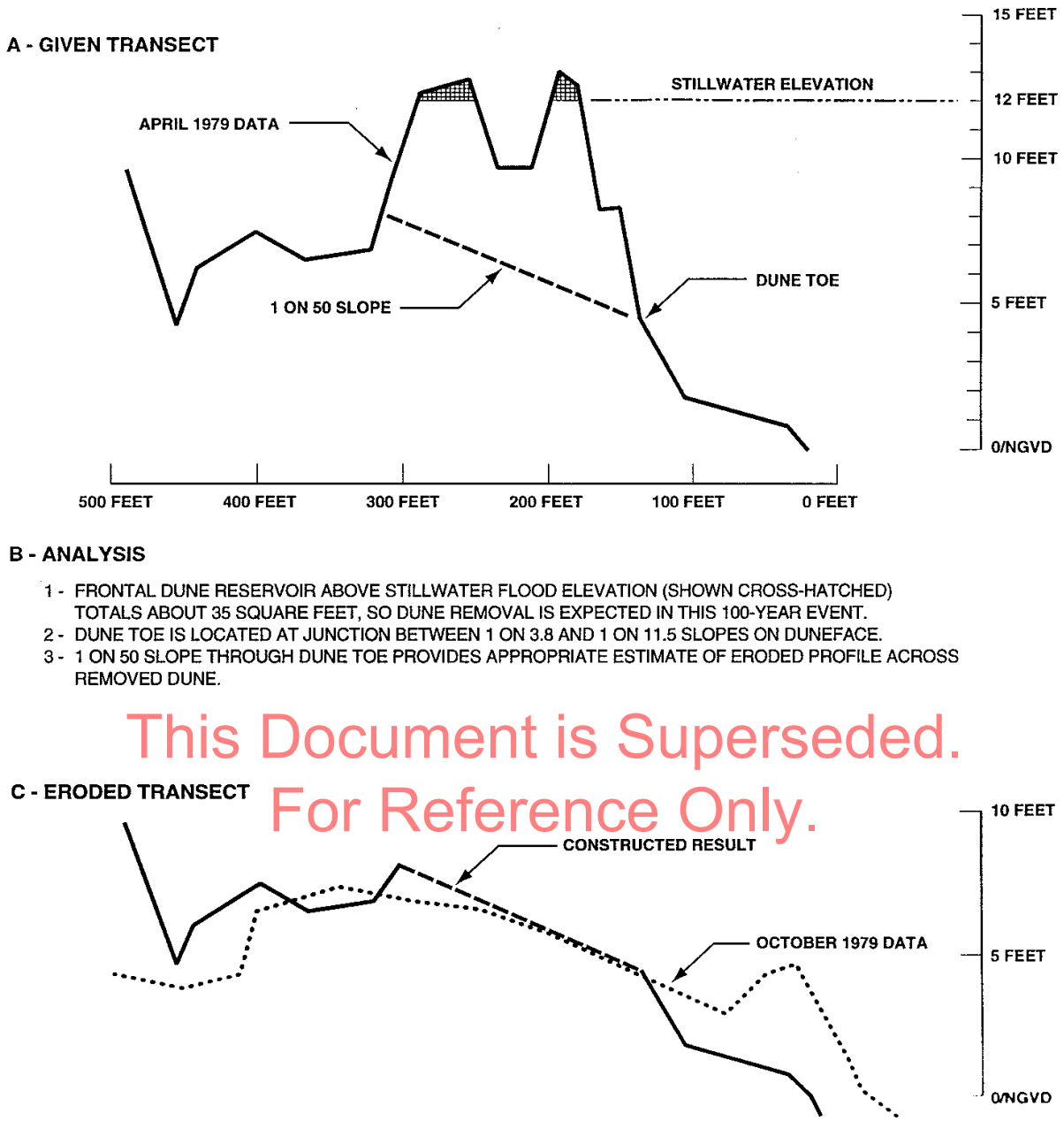


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**Figure D-6. Quantitative Example of Dune Removal Treatment for Alabama Profile Eroded by 1979 Hurricane Frederic. Situation Is Profile B-35 in Baldwin County, Alabama**

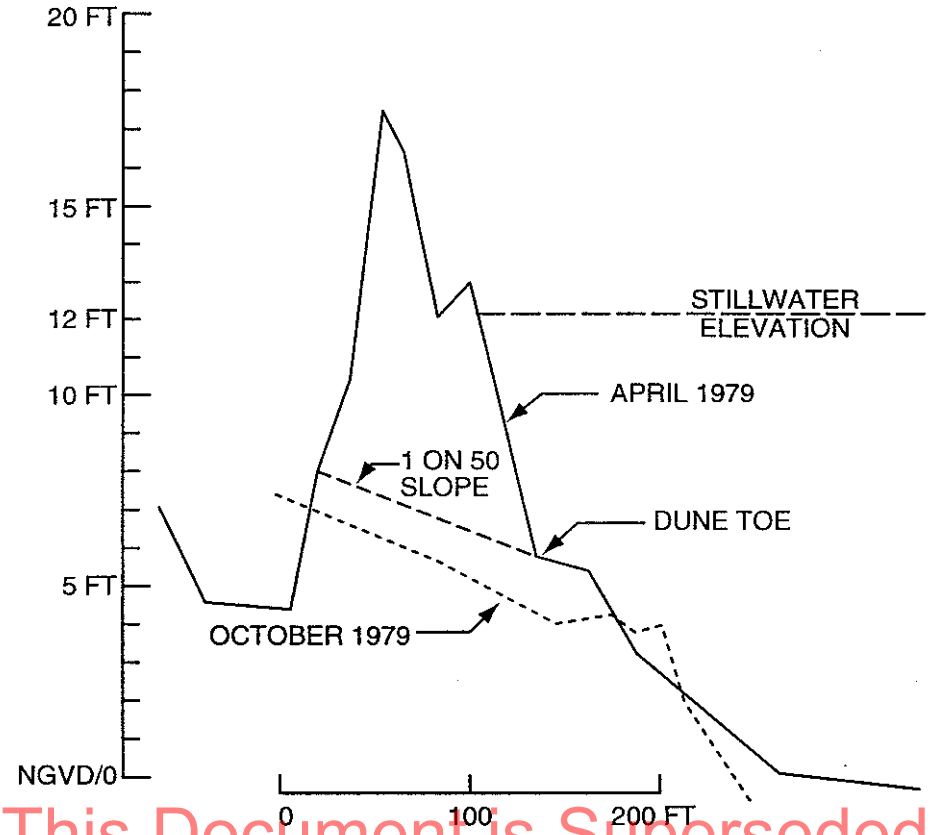


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**Figure D-7. Case of Relatively Large Dune Removed by 1979 Hurricane Frederic in Baldwin County, Alabama**

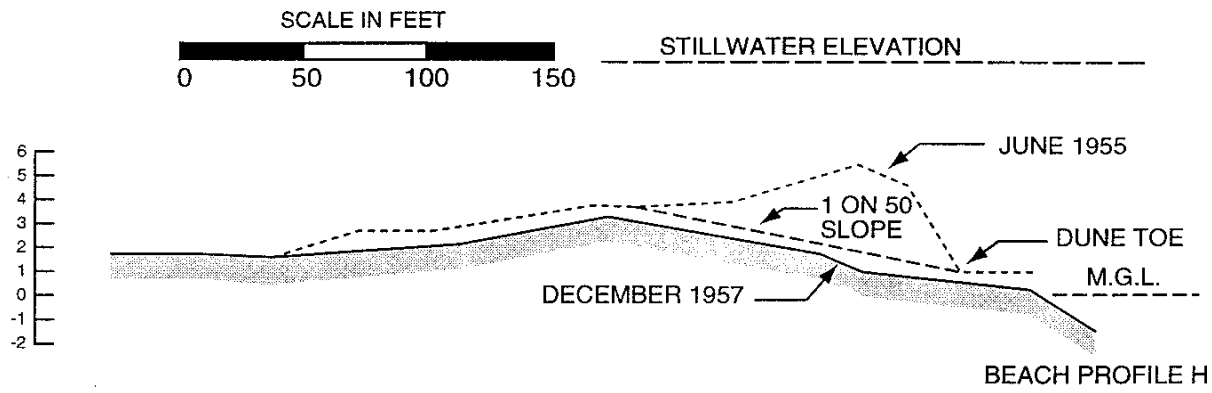


**Figure D-8. Erosion of Relatively Low Profile by 1957 Hurricane Audrey in Cameron Parish, Louisiana**

[February 2002]

### D.2.4.3 Treatment of Duneface Retreat

The procedure described here yields an eroded profile for duneface retreat in the 1-percent-annual-chance flood, for cases where the frontal dune reservoir is at least 540 square feet. During such retreat, the frontal dune barrier remains basically intact and eroded sand is transported in the seaward direction. The post-storm profile provides a balance between sand eroded from the duneface and sand deposited at lower elevations seaward of the dune.

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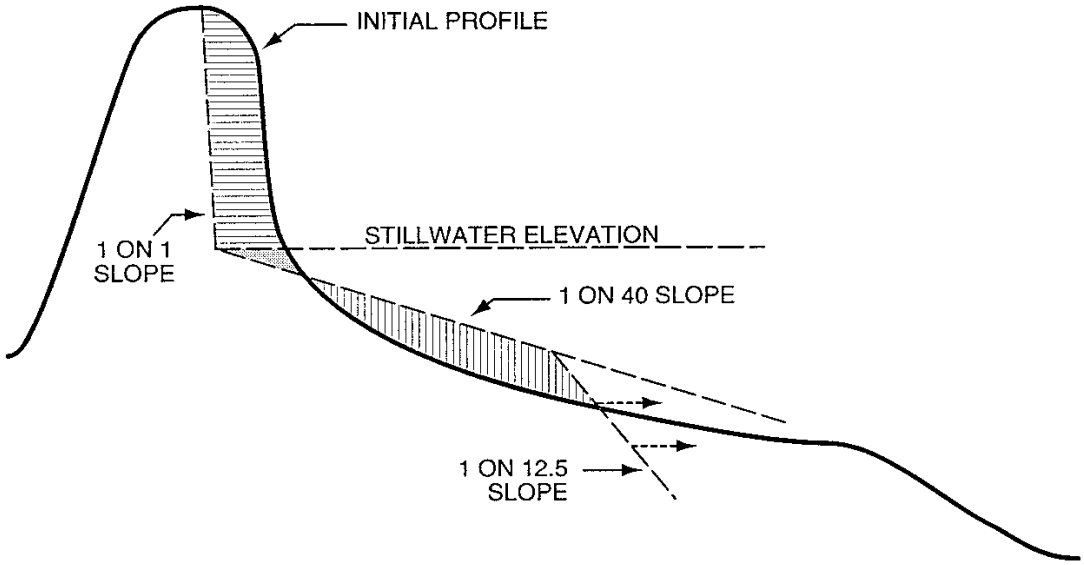
The following procedure for constructing the eroded profile constitutes a simplification of the dune retreat model developed by Delft Hydraulics Laboratory (DHL) of the Netherlands (Vellinga, 1986). Erosion above 1-percent-annual-chance SWEL is fixed at 540 square feet, to guarantee an appropriate amount for the U.S. Atlantic and Gulf coasts (FEMA, 1986 and November 1988). (In the DHL model, erosion is determined as the variable depending on specified storm and site conditions.)

Figure D-9 summarizes the simple procedure adopted to treat cases of duneface retreat. The eroded profile consists of three planar slopes: uppermost is a retreated duneface slope of 1:1, joining an extensive middle slope of 1:40, which is terminated by a brief segment with a slope of 1:12.5 at the limit to storm deposition. Upper dune erosion is specified to be 540 square feet above the 1-percent-annual-chance SWEL and in front of the 1:1 slope. Geometrical construction balances the nearshore deposition with the total dune erosion of somewhat more than 540 square feet by an appropriate seaward extension of the 1:40 slope. The resulting eroded profile is spliced onto the unchanged landward and seaward portions of the pre-storm profile. This procedure gives a complete profile suitable for use with the Wave Runup Model in assessing an appropriate flood elevation on the dune remnant.




PROCEDURE:

1 - CONSTRUCT RETREATED DUNEFACE WITH 540 $FT^2$ EROSION [ ] ABOVE 100-YEAR STILLWATER ELEVATION AND SEAWARD OF 1 ON 1 SLOPE.

2 - DETERMINE ADDITIONAL DUNE EROSION QUANTITY, SHOWN DOTTED, IN WEDGE BETWEEN STILLWATER ELEVATION, 1 ON 40 SLOPE, AND INITIAL PROFILE.

3 - BALANCE TOTAL DUNE EROSION WITH POSTULATED DEPOSITION [ ] BY APPROPRIATE PLACEMENT OF 1 ON 12.5 SLOPE AS LIMIT TO DEPOSITION.

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**Figure D-9. Procedure Giving Eroded Profile in Cases of Duneface Retreat, and Simplification of Dune Retreat Model Developed by Delft Hydraulics Laboratory of the Netherlands)**

Figure D-10 presents an example of duneface retreat according to the present procedure. This simple construction of a retreated dune profile gives appropriate eroded slopes important to the wave runup analysis of the remaining barrier. For this example, estimated erosion and deposition do not match well with those recorded, because there is a net sand loss shown on this profile and the event appears somewhat less extreme than a 1-percent-annual-chance flood (judging from reported characteristics of Hurricane Eloise). Where historical data on duneface retreat are available for comparison, agreement of estimated erosion slopes with those recorded should be considered of primary importance in verifying the present treatment. Actual quantities of dune erosion are subject to large variations in natural situations, and this procedure presumes a generally representative value for 1-percent-annual-chance flood conditions.

The Mapping Partner shall apply the basic procedure illustrated in Figure D-9 in estimating erosion of high open-coast headlands or bluffs of sandy material.

This modification to the DHL model eliminates potential problems associated with computation sensitivity to storm wave height and with uncertain capabilities for situations dissimilar to the Netherlands coast (Birkemeier et al., 1987; FEMA, November 1988). The other modifications of the model and treatment of duneface retreat have been implemented in an attempt to simplify the treatment by ignoring the variation of sand size and approximating the planar slope to the curved segment of the DHL post-storm profile.

In such cases, parallel retreat of the existing face slope should be presumed, rather than using the typical 1:1 slope for the escarpment on an eroded sand dune, because that existing slope reflects actual consolidation properties of the headland or bluff material.

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### D.2.4.4 Finalizing Erosion Assessment

Based on measured erosion along the Atlantic and Gulf coasts, the demarcation between duneface retreat and dune removal in a 1-percent-annual-chance flood has been set at a frontal dune reservoir of 540 square feet (FEMA, 1986 and November 1988). This quantitative criterion might appear too precisely stated, in view of potential inaccuracies in available dune topography, possible complications in delineating the effective frontal dune reservoir, and documented variability of dune erosion during extreme storms. In fact, the likelihood of duneface retreat or dune removal cannot be assessed with full certainty, so that validating the present erosion assessment by means of available evidence for a specific site is advisable.

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At many sites, some historical evidence may be available regarding the extent of flooding, erosion, and damage in an extreme event comparable to the local 1-percent-annual-chance flood. Then the erosion treatment giving results more consistent with historical records must be selected as appropriate. That choice may be relatively clear-cut, given potential differences in expected erosion and inland flood penetration for duneface retreat versus dune removal. Where available historical evidence is not definitive, the decision between retreat and removal on a given transect should be based solely on size of the frontal dune reservoir. Present procedures for erosion assessment are highly simplified, but provide an unbiased estimation and a level of detail appropriate to coastal FISs.

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### D.2.4.5 Wave Overtopping for Cases of Duneface Retreat

Where the erosion assessment indicates duneface retreat, an eroded dune remnant persists as an appreciable barrier to the 1-percent-annual-chance flood. However, storm wave action can result in occasional extreme runups overtopping that barrier, yielding floodwaters running off or ponding landward of the dune. DHL has determined the mean overtopping rate with storm waves incident on a typical duneface retreat geometry determined by the DHL (1983) to be

$$\overline{Q} = 5.26 \exp\left[-0.253\, F\right] . \qquad (1)$$

Here the overtopping rate $\overline{Q}$1 has units of cubic feet per second per foot alongshore (cfs/ft), and $F$ is maximum height (in feet) of the dune remnant above SWEL.

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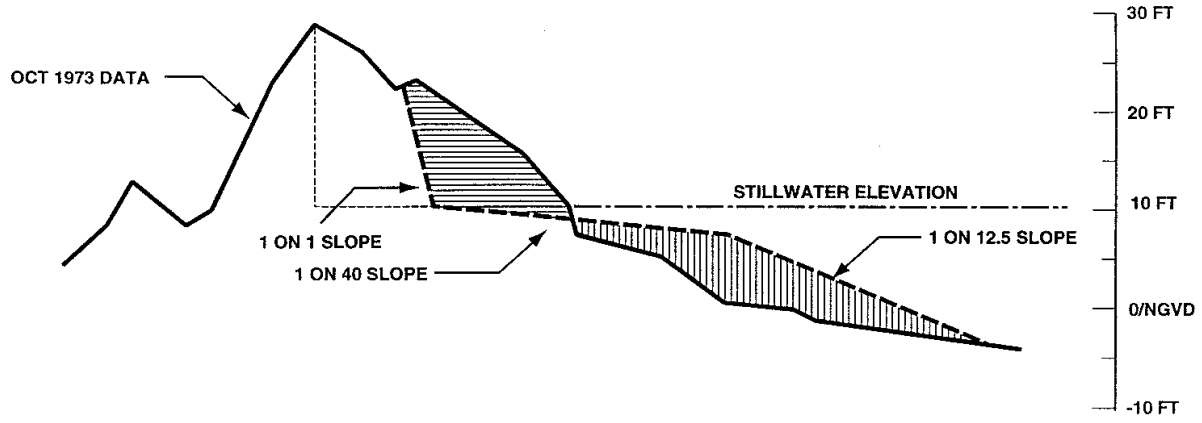
**A - GIVEN TRANSECT**




**B - ANALYSIS**

1 - FRONTAL DUNE RESERVOIR, OUTLINED BY--- , GREATLY EXCEEDS 540 $FT^2$ SO DUNEFACE WILL RETREAT.
2 - SPECIFYING EROSION ABOVE STILLWATER ELEVATION AS 540 $FT^2$, TOTAL DUNE EROSION ABOVE TWO UPPERMOST SLOPES IS FOUND TO BE APPROXIMATELY 620 $FT^2$.
3 - EROSION [▤] IS MADE TO EQUAL DEPOSITION [||||||||] BY EXTENDING MIDDLE (1 ON 40) SLOPE.

**C - ERODED TRANSECT**

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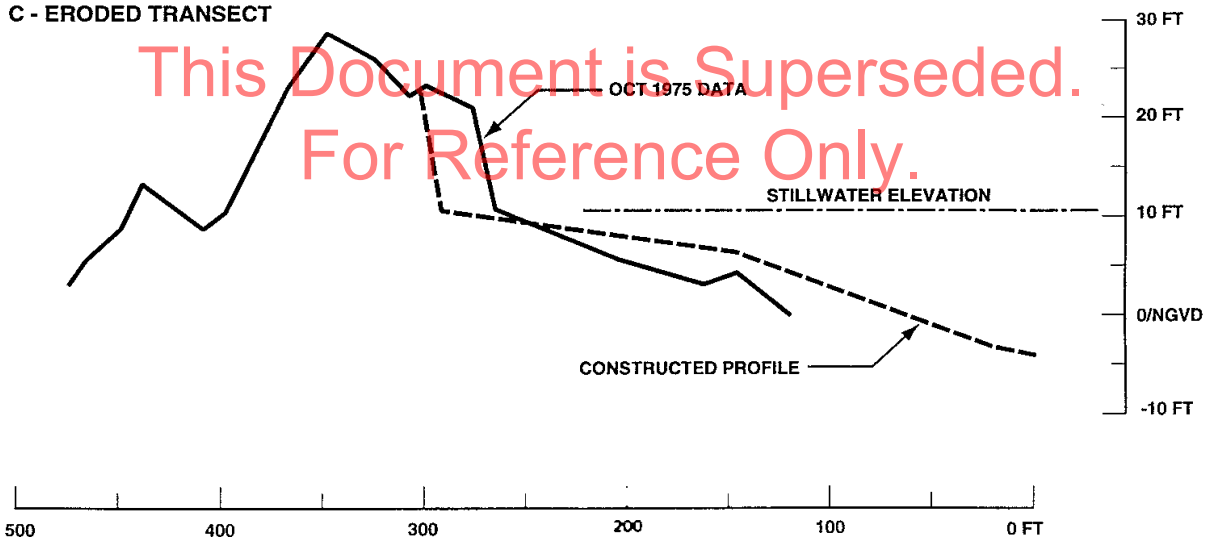


**Figure D-10. Example of Duneface Retreat Treated by Simplified version of D.H.L. model, with erosion Above SWEL Fixed at 540 Square Feet. Situation Is Profile R-105 in Walton County, Florida, Surveyed Before and After 1975 Hurricane Eloise**

This result was measured in DHL tests scaled to reproduce a specific extratropical storm on the Dutch seacoast, with a significant deep-water wave height of 25 feet and a peak wave period of 12 seconds. Those wave conditions seem roughly representative for the 1-percent-annual-chance flood along U.S. seacoasts, although expected wave characteristics will differ between hurricanes and extratropical storms at various sites. Recorded rates of overtopping can show sizable departures from the expected mean even with steady flood conditions (Goda, 1985; Owen, 1980).

Despite uncertainties about actual overtopping rates for a dune remnant, the equation gives a useful basis for outlining expected effects. The order of magnitude for severe overtopping may be taken as 1 cfs/ft, past allowable thresholds for structural integrity with bare soil behind steep barriers exposed to storm waves (Goda, 1985). From Equation 1, $\overline{Q}2$ of approximately 1 cfs/ft corresponds to $F$ of approximately 7 feet, so retreated remnants with less relief above the 1-percent-annual-chance SWEL certainly require consideration of possible flood hazards landward of the dune. Appropriate treatments for ponding or runoff behind barriers are outlined in Subsection D.2.6.

[February 2002]

## D.2.5 Wave Runup, Setup, and Overtopping

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Wave runup is the uprush of water from wave action on a shore barrier intercepting stillwater level. The water wedge generally thins and slows during its excursion up the barrier, as residual forward momentum in wave motion near the shore is fully dissipated or reflected. The notable characteristic of this process for present purposes is the wave runup elevation, the vertical height above stillwater level ultimately attained by the extremity of uprushing water. Wave runup at a shore barrier can provide flood hazards above and beyond those from stillwater inundation and incident wave geometry, as illustrated in Figure D-11.

Two additional phenomena, wave setup and wave overtopping, may require explicit consideration for adequate treatment of the coastal flood hazards linked to wave runup. Wave setup generates a mean water surface elevated above the SWFL, caused by accumulation of water against a barrier exposed to wave heights attenuating in shallow water. Wave overtopping consists of any wave-induced flow passing over the barrier crest, so that flood water may exhibit wave, sheet flow, or ponding characteristics over an inland area. These phenomena and their quantitative evaluation will be addressed later in this Appendix.

The extent of runup can vary greatly from wave to wave in storm conditions, so that a wide distribution of wave runup elevations provides the precise description for a specific situation. Current policy for the NFIP is that the mean runup elevation (rather than some occasional extreme) for a situation is appropriate in mapping coastal hazards of the 1-percent-annual-chance flood.

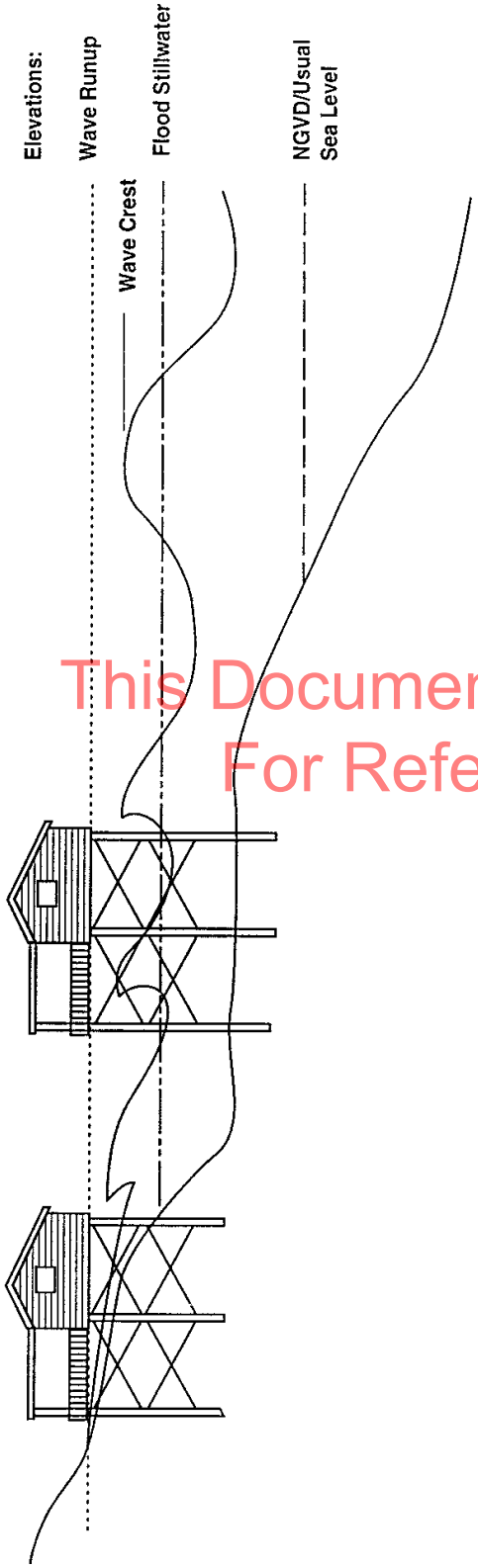


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**Figure D-11. Schematic Illustration of Wave Effects Extending Above and Landward of Stillwater Intercept on Transect**

[February 2002]

### D.2.5.1 Wave Runup Model Description

The current version of the FEMA Wave Runup Model, RUNUP 2.0, may be run either on a minicomputer (e.g., DEC VAX 11/750) or on an IBM-compatible personal computer (PC or PC/AT). Given the flood level, shore profile and roughness, and incident wave condition described in deep water, the program computes by iteration a wave runup elevation fully consistent with the most detailed guidance available (Stoa, 1978). This determination includes an analysis separating the profile into an approach segment next to the steeper shore barrier, and interpolation between runup guidance for simple configurations bracketing the specified situation.

Some additional description of the workings of the Wave Runup Model can assist informed preparation of input and interpretation of output. The incorporated guidance gives runup elevation as a function of wave condition and barrier slope, for eight basic shore configurations distinguished by water depth at the barrier toe, along with the approach geometry. Where those basic geometries do not appropriately match the specified profile, reliance is placed on the composite slope method (Saville, 1958); this assumes the input shore profile (composite slope) is equivalent to a hypothetical uniform slope, as shown in Figure D-12. The runup elevations are derived from laboratory measurements in uniform wave action, rather than the irregular storm waves usually accompanying a flood event. Runup guidance for uniform waves, however, also pertains to the mean runup elevation from irregular wave action with identical mean wave height and mean wave period. Figure D-13 presents an overview of the basic computation procedure within RUNUP 2.0.

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Basic empirical guidance incorporated within this computer model generally does not extend to vertical or nearly vertical flood barriers. For such configurations, RUNUP 2.0 usually will provide a runup elevation, but the result may be misleading because reliance on the composite-slope method can yield an underestimate of actual wave runup with the abrupt barrier. Where a vertical wall exists on a transect, the Mapping Partner shall develop a runup estimate using specific guidance in Figure D-14, taken from the *Shore Protection Manual* (USACE, 1984). As within RUNUP 2.0, these empirical results for uniform waves should be utilized by specifying mean wave height and mean wave period for entry, and taking the indicated runup as a mean value in storm wave action. Shore configurations with a vertical wall are also addressed separately in Subsection D.2.5.7.

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### D.2.5.2 Wave Runup Model Input Preparation

The input to the Wave Runup Model is done by transects. As specified in Subsection D. 2.2, the Mapping Partner shall locate transects along the shoreline. Because the runup results are very sensitive to shore slope or steepness, it is important to have at least one transect for each distinct type of shore geometry. Often, areas with similar shore slopes are located throughout a community, and the results of one transect can be applied to all the areas that are similar. This is

especially typical of New England communities with rocky bluffs. When the Wave Runup Model is being applied to dune remnants where eroded slopes are fairly uniform, transect location is governed by the upland land-cover characteristics, which are major considerations in

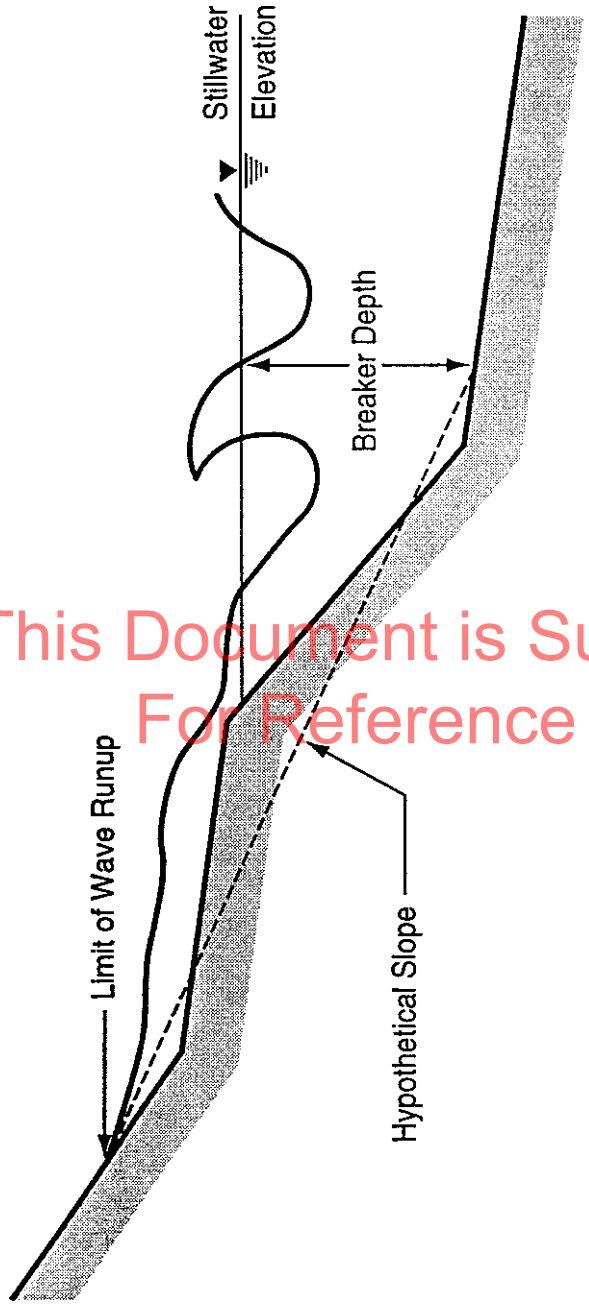


**Figure D-12. Hypothetical Slope for Determining Wave Runup on Composite Profiles**

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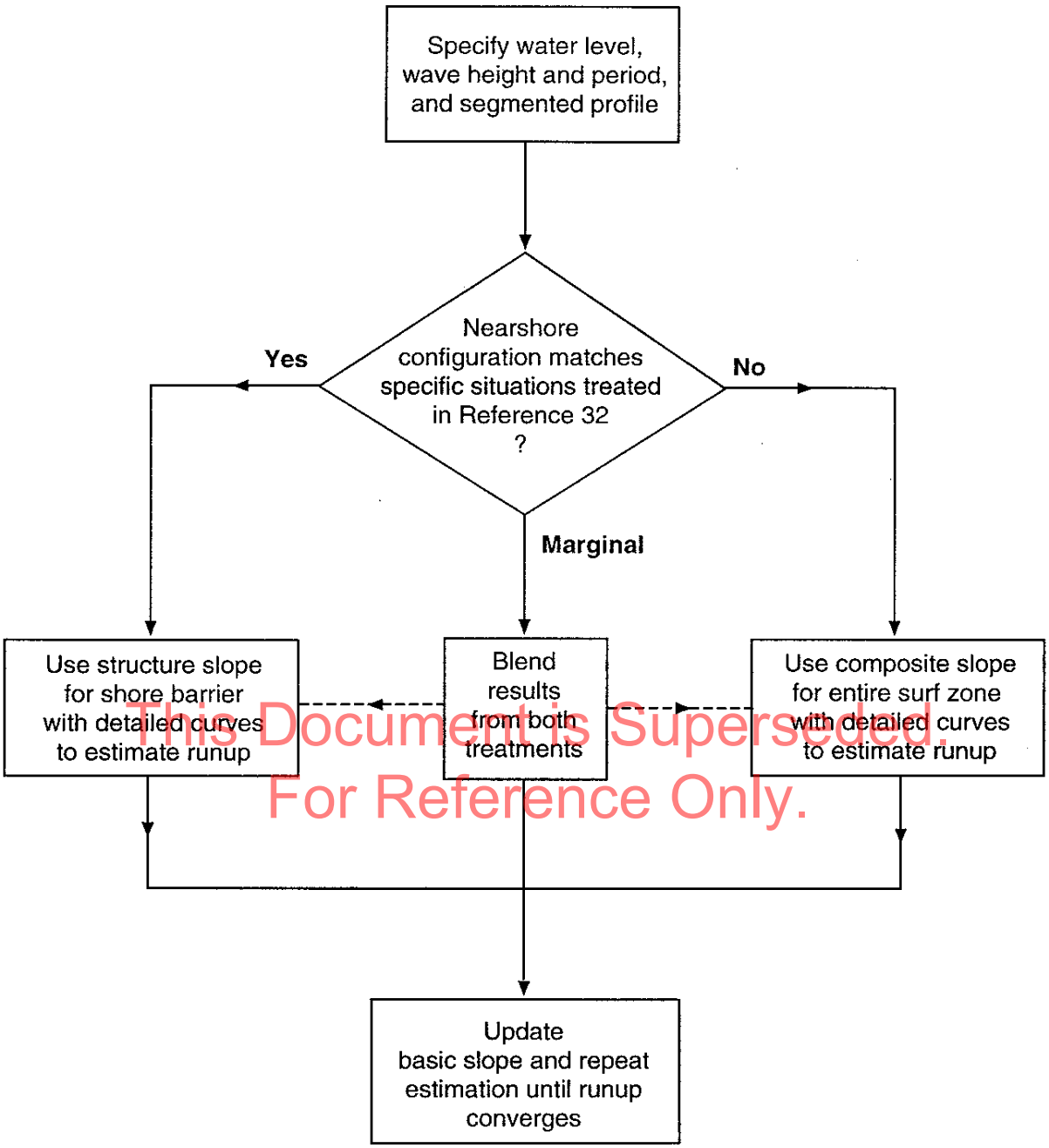


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**Figure D-13. Overview of Computation Procedure Implemented in Modified FEMA Wave Runup Model**

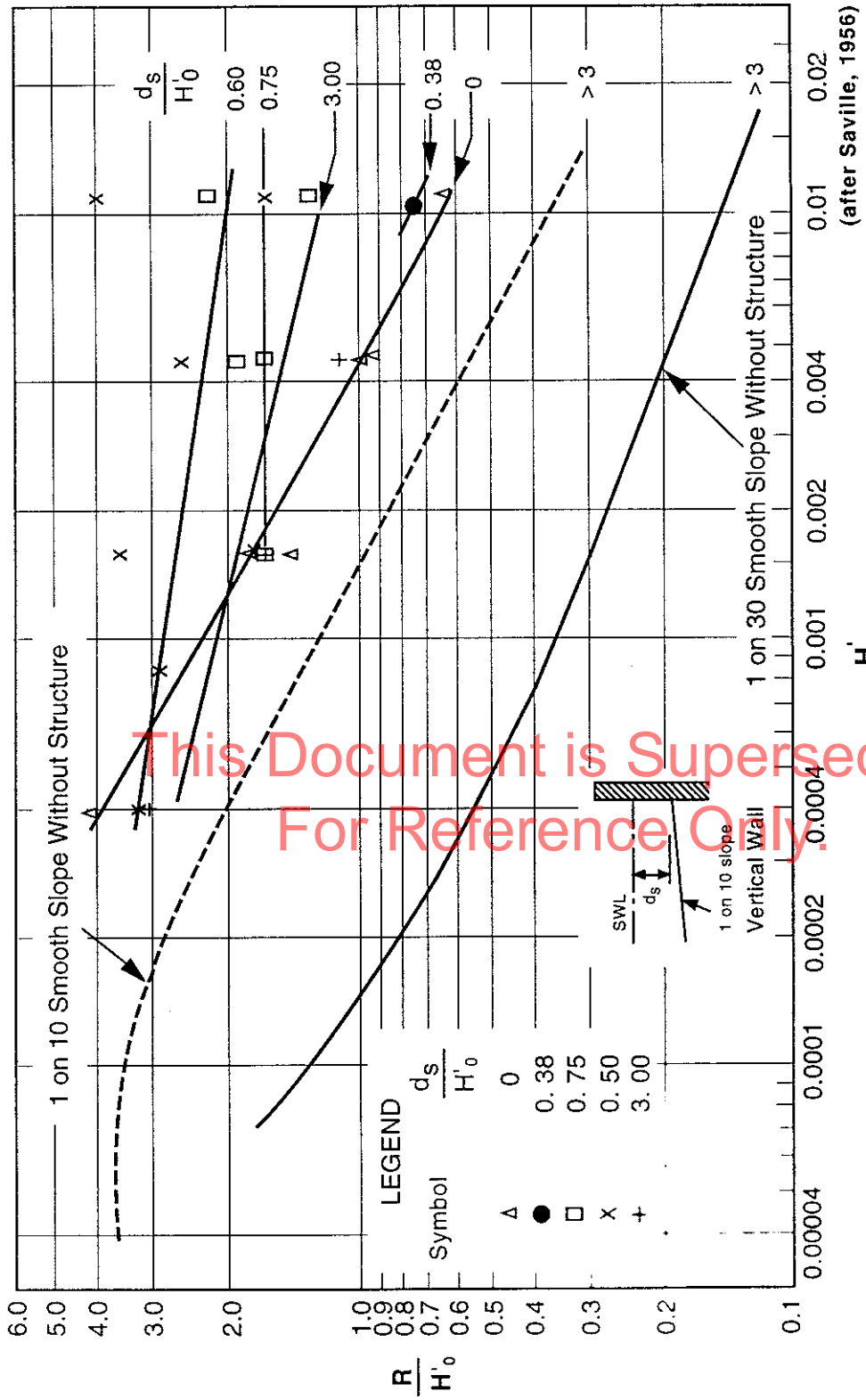


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**Figure D-14. Wave Runup Guidance from Vertical Wall, From *Shore Protection Manual* (USACE, 1984)**

in the WHAFIS model.

The ground profile for the transect is plotted from the topography and bathymetry after the data have been referenced to the National Geodetic Vertical Datum (NGVD). The profile must extend from an elevation below the breaker depth to an elevation above the limit of runup or to the maximum ground elevation. An adequate vertical extent for the transect description will usually be 1.5 times the wave height above and below the SWEL. If the landward profile does not extend above the computed runup (30 feet NGVD is commonly a maximum), it will be assumed that the last positive slope segment continues indefinitely. This is very common with low barriers, so the Mapping Partner shall select the last slope carefully so it is representative. To complete the description, each slope segment of the profile will need a roughness coefficient, with some common values presented in Table D-3. The roughness coefficient must be between zero (maximum roughness) and one (hydraulically smooth), and values for slope segments above the SWFL control the estimated runup. The roughness coefficient *(r)* is used as a multiplier for runup magnitude *(R)* defined on a smooth barrier to estimate wave runup with a rough barrier.

**Table D-3. Values for Roughness Coefficient in Wave Runup Computations**

| ROUGHNESS COEFFICIENT | DESCRIPTION OF BARRIER SURFACE |
|---|---|
| 1.00 | Sand; smooth rock, concrete, asphalt, wood, fiberglass |
| 0.95 | Tightly set paving blocks with little relief |
| 0.90 | Turf, closely set stones, slabs, blocks |
| 0.85 | Paving blocks with sizable permeability or relief |
| 0.80 | Steps; one stone layer over impermeable base; stones set in cement |
| 0.70 | Coarse gravel; gabions filled with stone |
| 0.65 | Rounded stones, or stones over impermeable base |
| 0.60 | Randomly placed stones, two thick on permeable base; common rip-rap installations |
| 0.50 | Cast-concrete armor units: cubes, dolos, quadripods, tetrapods, tribars, etc. |

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Transects are approximated by the minimum adequate number of linear segments, up to a limit of 20. Segments may be horizontal, or higher at the landward end; portions with opposite inclination should be represented as horizontal when developing the transect approximation. Using many linear segments to represent a transect can be wasted effort, because the Wave Runup Model may combine adjacent segments in defining the appropriate approach and barrier extents. With the runup computation procedure, the Mapping Partner shall apply engineering judgment to transect representation to assist in obtaining the most valid estimate of wave runup elevation.

The input transect must reflect wave-induced modifications expected during the 1-percent-annual-chance event, including erosion on sandy shores with dunes. The Mapping Partner shall represent only coastal structures expected to remain intact throughout the 1-percent-annual-chance event on a specific transect. Besides the transect specification, other required input data for the Wave Runup Model are the 1-percent-annual-chance SWEL and the incident mean wave condition described in deep water. The specified SWEL should exclude any contributions from

wind-wave effects. If available elevations include wave setup, the Mapping Partner shall remove that component before using this model so that calculated runup elevations do not indicate a doubled wave setup. Basic empirical guidance relates runup at a barrier to the water level in the absence of wave action and thus includes the wave setup component.

The mean wave condition to be specified for valid results with the Wave Runup Model may be derived from other common wave descriptions by simple relationships. Wave heights in deep water generally conform to a Rayleigh probability distribution, so that mean wave height equals 0.626 times either the significant height based on the highest one-third of waves or the zero-moment height derived from the wave energy spectrum. No exact correspondence between period measures exists; but, mean wave period usually can be approximated as 0.85 times the significant wave period or the period of peak energy in the wave spectrum.

Table D-4 lists a series of wave height and period combinations, of which one should be fairly suitable for runup computations at fully exposed coastal sites (depending on the local storm climate). These mean wave conditions have wave steepness values typical of U.S. hurricanes or within 30 percent of a fully arisen sea for extratropical storms. Commonly, the Mapping Partner may have some difficulty in specifying a precise wave condition as accompanying the 1-percent-annual-chance flood. In that case, is the Mapping Partner also shall consider wave heights and periods both 5 percent higher and 5 percent lower than that selected (or whatever percentages suit the level of uncertainty) and shall run the model with all nine combinations of those values. The average of computed runup values then provides a suitable estimate for mean runup elevation. A wide range in computed runups signals the need for more detailed analysis of expected wave conditions or for reconsideration of the transect representation.

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**Table D-4. Appropriate Wave Conditions for Runup Computations Pertaining to 1-Percent-Annual-Chance Event in Coastal Flood Insurance Studies**

| MEAN WAVE PERIOD (SECONDS) | MEAN DEEP WATER WAVE HEIGHT (FEET) |
|---|---|
| **HURRICANES** | |
| 8 | 12 |
| 9 | 15.5 |
| 10 | 19 |
| 11 | 23 |
| 12 | 27.5 |
| **EXTRATROPICAL STORMS** | |
| 11 | 18 |
| 12 | 21.5 |
| 13 | 25 |
| 14 | 29 |
| 15 | 33.5 |

[February 2002]

### D.2.5.3 Wave Runup Model Operation

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The input to the FEMA Wave Runup Model consists of several separate lines specifying an individual transect and the hydrodynamic conditions of interest within particular columns. All input information is echoed in an output file, which also includes computed results on wave breaking and wave runup.

The input format is outlined in Table D-5. The first two lines of the input give the Name and Job Description, which must be included for each transect. The next line of input is the Last Slope, which contains the cotangent of the shore profile continuing from the most landward point provided. This is followed by the profile points, which define the nearshore profile in consecutive order from the most seaward point. Each line gives the elevation and station of a profile point and the roughness coefficient for the segment between that point and the following point. The roughness coefficient on the last profile line is for the continuation defined in the Last Slope line. The number of profile points cannot exceed 20. The final input is the series of hydrodynamic conditions of interest. Each line here contains the SWEL along with a mean wave height in deep water and a mean wave period.

**Table D-5. Description of Five Types of Input Lines for Wave Runup Model**

Name Line

This line is required and must be the first input line.

| Columns | Contents |
|---|---|
| 1-2 | Blank |
| 3-28 | Client's Name |
| 29-60 | Blank |
| 61-70 | Engineer's Name |
| 71-80 | Job Number |

Job Description Line

| Columns | Contents |
|---|---|
| 1-2 | Blank |
| 3-76 | Project description or run identification |
| 77-80 | Run Number |

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Last Slope Line

This line is required and defines the slope immediately landward of the profile actually specified in detail.

| Columns | Contents |
|---|---|
| 1-4 | Slope (horizontal over vertical or cotangent) of profile continuation |
| 5-80 | Blank |

Profile Lines

These lines must appear in consecutive order from the most seaward point landward. Each line has the elevation and station of a profile point and the roughness coefficient for the section between that point and the following point. The roughness coefficient on the last profile line is for the continuation defined in the Last Slope Line. The Mapping Partner shall ensure that at least one profile point with a ground elevation greater than the SWEL is specified. The number of Profile Lines cannot exceed 20.

| Columns | Contents |
|---|---|
| 1 | Last point flag. The most landward point on the profile is indicated by a 1. If not the last point, leave blank. |

| | |
|---|---|
| 2 | Blank |
| 3-7 | Elevation with respect to NGVD, in feet |
| 8 | Blank |
| 9-14 | Horizontal distance. It is common to assign the shoreline (elevation 0.0) as Point 0 with seaward distances being negative and landward distances positive. |
| 15 | Blank |

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**Table D-5. Description of Five Types of Input Lines for Wave Runup Model (Cont'd).**

| Columns | Contents |
|---|---|
| 16-20 | Roughness coefficient in decimal form between 0.00 (most rough) and 1.00 (smooth). |
| 21-80 | Blank |

Water Level and Wave Parameter Lines

These lines specify hydrodynamic conditions for runup calculations on each profile. Namely, 1-percent-annual-chance SWEL along with mean wave height and period for deep water. Typically, SWEL remains constant for a given profile, while the selected wave conditions closely bracket that expected to accompany the 1-percent-annual-chance flood. A maximum of 50 of these lines can be input for each profile.

| Columns | Contents |
|---|---|
| 1 | Last line, new transect flag. A 1 indicates the last line for a given transect and notifies that another transect is following. If not the last line, or if the last line of the last transect, leave blank. |
| 2-6 | SWEL with respect to NGVD, in feet. |
| 7 | Blank |
| 8-12 | Deepwater mean wave height, $\overline{H}$3o, in feet, greater than 1 foot |
| 13 | Blank |
| 14-18 | Mean wave period, $\overline{T}$4, in seconds |
| 19-80 | Blank |

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The output as shown in Table D-6 has two parts. The first page is a printout of the transect listed as a numbered set of profile points, cotangents (slopes) of the segments, and the roughness coefficient for each segment. The second page is the output table of computed results for each set of conditions: the values of runup elevation and breaker depth, each with respect to the specified SWEL, along with an identification of the segment numbers giving the seaward limit to wave breaking and the landward limit to mean wave runup.

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### D.2.5.4 Wave Runup Model Output Messages

Several output messages alert the user to specific problems encountered in running the program. All but the last three indicate that the program has stopped execution without completing runup calculations.

- "NEGATIVE RUN PARAMETER, PROGRAM STOPS"

An input value of wave height or wave period is read as negative or zero. Check that the input has been entered in the correct columns.

- "MORE THAN 20 POINTS IN PROFILE, PROGRAM STOPS"

  The program accepts a maximum input of 20 points defining the nearshore profile. This encourages a profile approximation that is not overly detailed, because each transect is to represent an extensive area.

- "**** $H_o/L_o$ LESS THAN 0.002 ****" or
  "**** $H_o/L_o$ GREATER THAN 0.07 ****"

  These limits on wave steepness pertain to the extent of incorporated guidance on breaker location. They should be adequate to include appropriate mean wave conditions for extreme events and also conform to the usual limits in detailed guidance on wave runup elevations.

- "DATA EXCEEDED TABLE"

  An entry into subroutine LOOK of the program is not within the parameter bounds of the data table from which a value is sought.

- "SOLUTION DOES NOT CONVERGE"

  After 10 iterations, the current and previous estimates of runup elevation continue to differ by more than 0.15 foot, and both values are provided in the output table. The calculation is usually oscillating between these two runup estimates when this occurs.

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- "COMPOSITE SLOPE USED BUT WAVE MAY REFLECT, NOT BREAK"

  The output runup elevation relies to some extent on a composite-slope treatment, but the overall slope is steep enough that the specified wave may reflect from the nearshore barrier. Thus, the application of a calculated breaker depth in determining overall slope and runup elevation is questionable.

- "WARNING; COMPOSITE SLOPE USED, BUT INPUT PROFILE DOES NOT EXTEND TO BREAKER DEPTH"

  If the input profile does not extend seaward of the breaker depth, an incorrect breaker depth may be computed and the associated runup elevation will also be incorrect. The input profile should include bathymetry to 30 or 40 feet in depth.

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### D.2.5.5 Wave Runup in Special Situations

To interpret and apply the calculated results properly, the Mapping Partner shall examine the output of the Wave Runup Model carefully for each situation. One important consideration is that a mean runup elevation below the crest of a given barrier does not necessarily imply the barrier will not occasionally be overtopped by floodwaters; the necessary supplementary examination of wave overtopping is addressed in Subsection D.2.5.7. Other cases may yield

```
CLIENT- FEMA                        ** WAVE RUNUP-VERSION 2.0  ** ENGINEERED BY DAB       JOB 1
PROJECT-Runup calculations on Eroded Transect                                    RUN 1    PAGE  1

*****************************************************************************************************************

                    CROSS SECTION PROFILE

                 LENGTH    ELEV.     SLOPE      ROUGHNESS

        1       -2670.0    -34.0
                                      97.50        1.00
        2       -1500.0    -22.0
                                      76.25        1.00
        3        -585.0    -10.0
                                      72.50        1.00
        4        -150.0     -4.0
                                      36.43        1.00
        5         -99.0     -2.6
                                      42.22        1.00
        6          53.0      1.0
                                      24.64        1.00
        7         223.0      7.9
                                      39.60        1.00
        8         322.0     10.4
                                        .99        1.00
        9         335.0     23.5
                                      10.00        1.00
       10         350.0     25.0

                     LAST SLOPE   1.00     LAST ROUGHNESS   1.00
```

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**Table D-6. Output Example for the FEMA Wave Runup Model**

results of more immediate concern, in that the Wave Runup Model may calculate a runup elevation exceeding maximum barrier elevation; this outcome can occur because the program assumes the last positive slope to continue indefinitely. For bluffs or eroded dunes with negative landward slopes, a general rule has been used that limits the wave runup elevation to 3 feet above the maximum ground elevation. When the runup overtops a barrier such as a partially eroded bluff or a structure, the floodwater percolates into the bed and/or runs along the back slope until it reaches another flooding source or a ponding area. The runoff areas are usually designated as Zone AO with a depth of 1, 2, or 3 feet. Ponding areas are designated as Zone AH (depth of 3 feet or less) with a BFE. Standardized procedures for the treatment of sizable runoff and ponding are presented in Appendix E of these Guidelines.

A fairly typical situation on the Atlantic and Gulf coasts is that wave runup exceeds the barrier top and flows to another flooding source such as a bay, river, or backwater. It may not be necessary in this situation to compute overtopping rates and ponding elevations; only the flood hazard from the runoff must be determined. Simplified procedures have been used to determine an approximate depth of flooding in the runoff area (Williams, 1983). These procedures are illustrated in Figure D-15 and discussed below.

When the runup computed on the imaginary extension of the last positive slope is greater than or equal to 3 feet above the maximum ground elevation, the maximum runup shall be 3 feet above the ground crest elevation. This elevation decays to 2 feet above the ground profile at 50 feet behind the crest and continues at this depth until it encounters other flooding. Computed runup is not adjusted if it is less than 3 feet above the ground crest. In the same initial 50 feet, this elevation decays to 1 foot above the ground and continues at this depth until it encounters other flooding. The runoff area from the ground crest to the limit of the other flooding is designated Zone AO with the appropriate depth of flooding.

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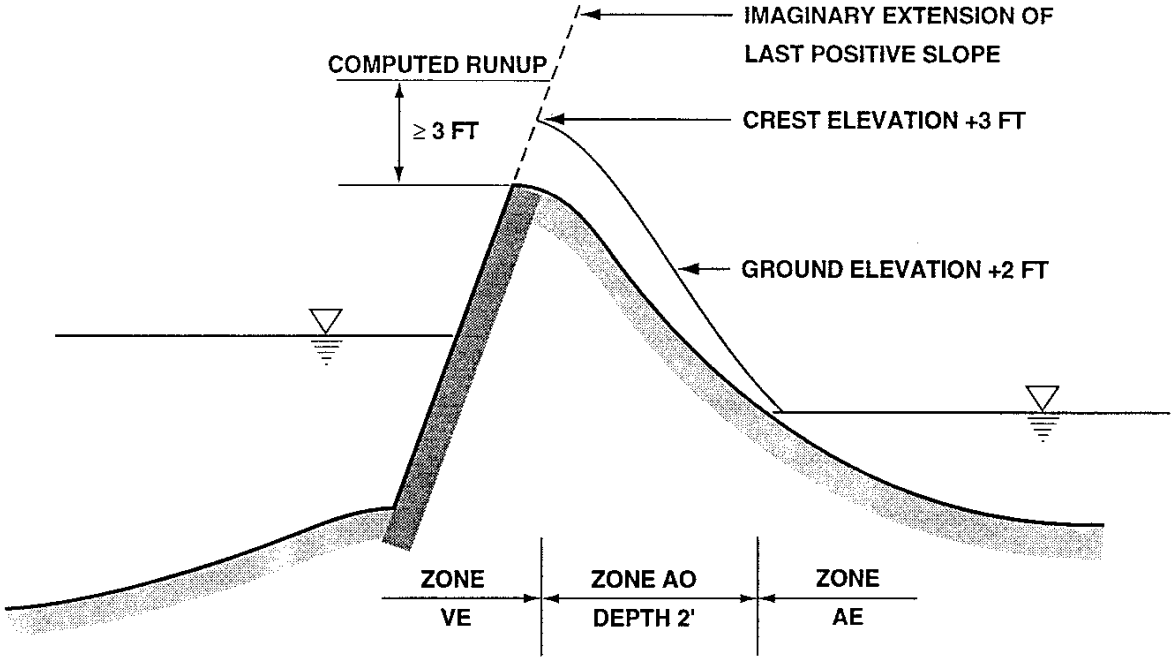
A distinct type of overflow situation can occur at low bluffs or banks backed by a nearly level plateau, where calculated wave runup may appreciably exceed the top elevation of the steep barrier. A memorandum entitled “Special Computation Procedure Developed for Wave Runup Analysis for Casco Bay, FIS - Maine, 9700-153” provides a simple procedure to determine realistic runup elevations for such situations, as illustrated in Figure D-16 (French, 1982). An extension to the bluff face slope permits computation of a hypothetical runup elevation for the barrier, with the imaginary portion given by the excess height $R' = (R\text{-}C)$ between calculated runup and the bluff crest. Using that height $R'$ and the plateau slope $m$, Figure D-17 defines the inland limit to wave runup, $X$, corresponding to runup above the bluff crest of ($mX$) or an adjusted runup elevation of $R_a = (C + mX)$. This procedure is based on a Manning's "n" value of 0.04 with some simplifications in the energy grade line and is meant for application only with positive slopes landward of the bluff crest. A different treatment of wave overflow onto a level plateau, for possible FIS usage, is provided in “Overland Bore Propagation Due to an Overtopping Wave” (Cox & Machemehl, 1986).



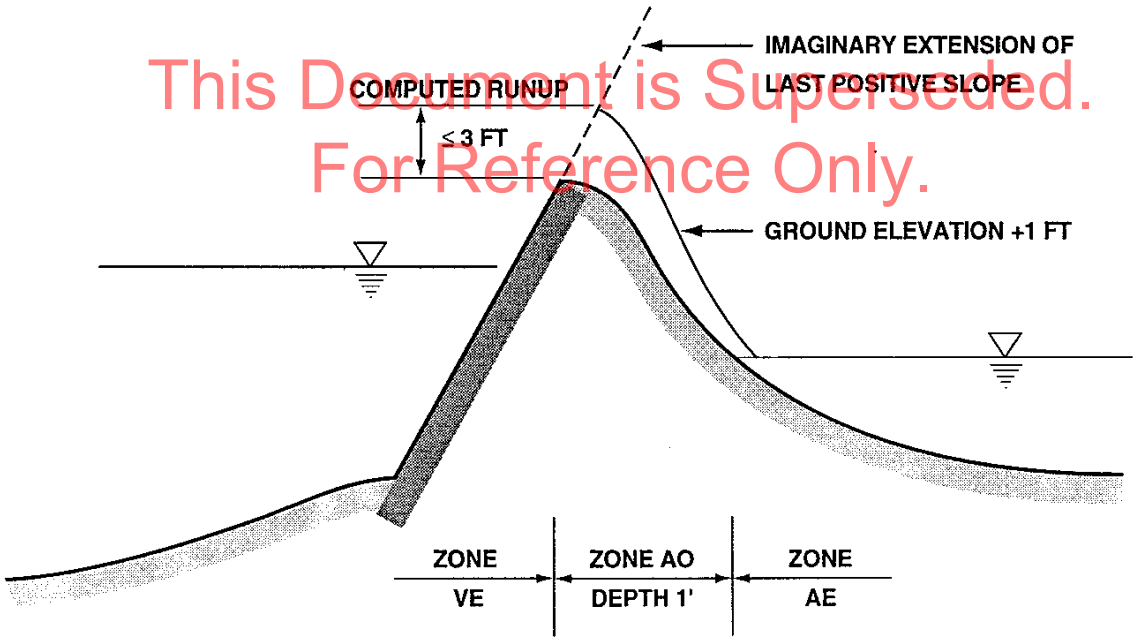




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**Figure D-15. Simplified Runoff Procedures (Zone AO)**

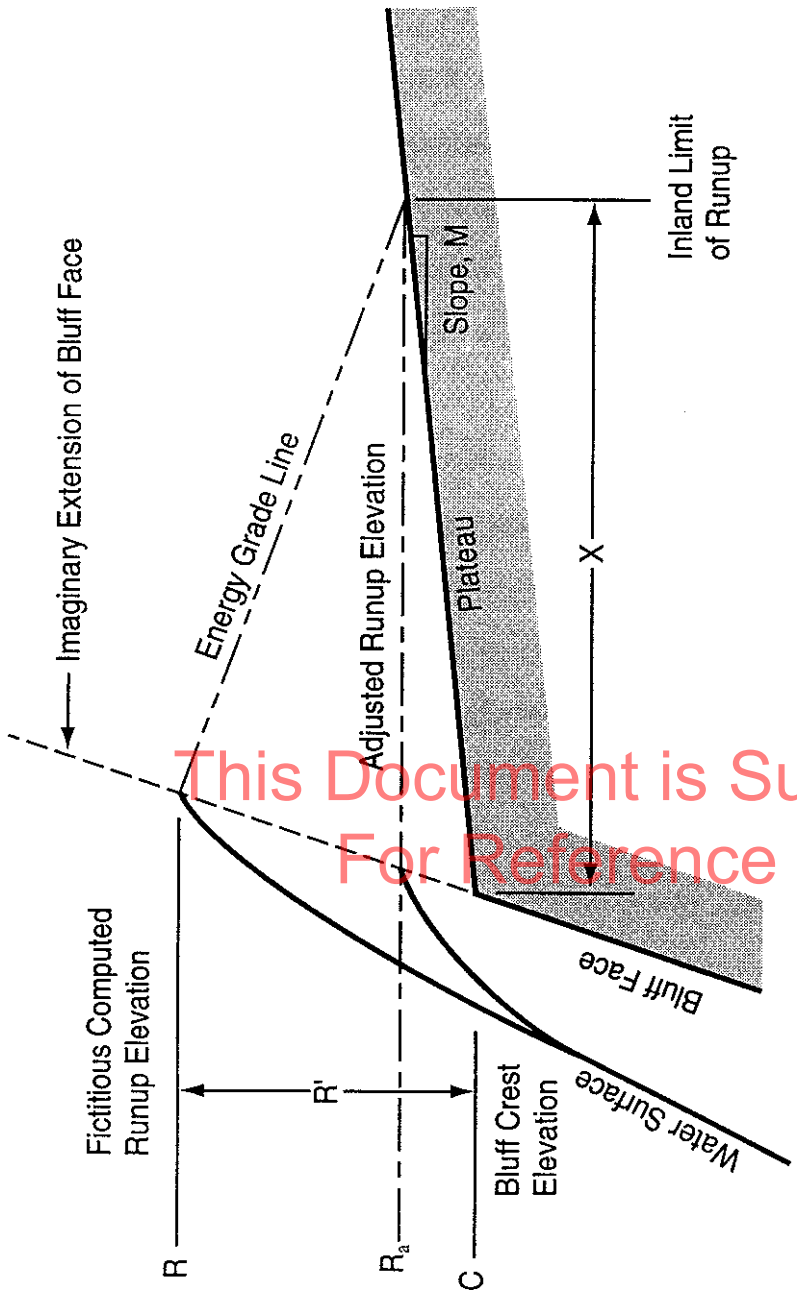


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**Figure D-16. Treatment of Runup onto Plateau above Low Bluff**

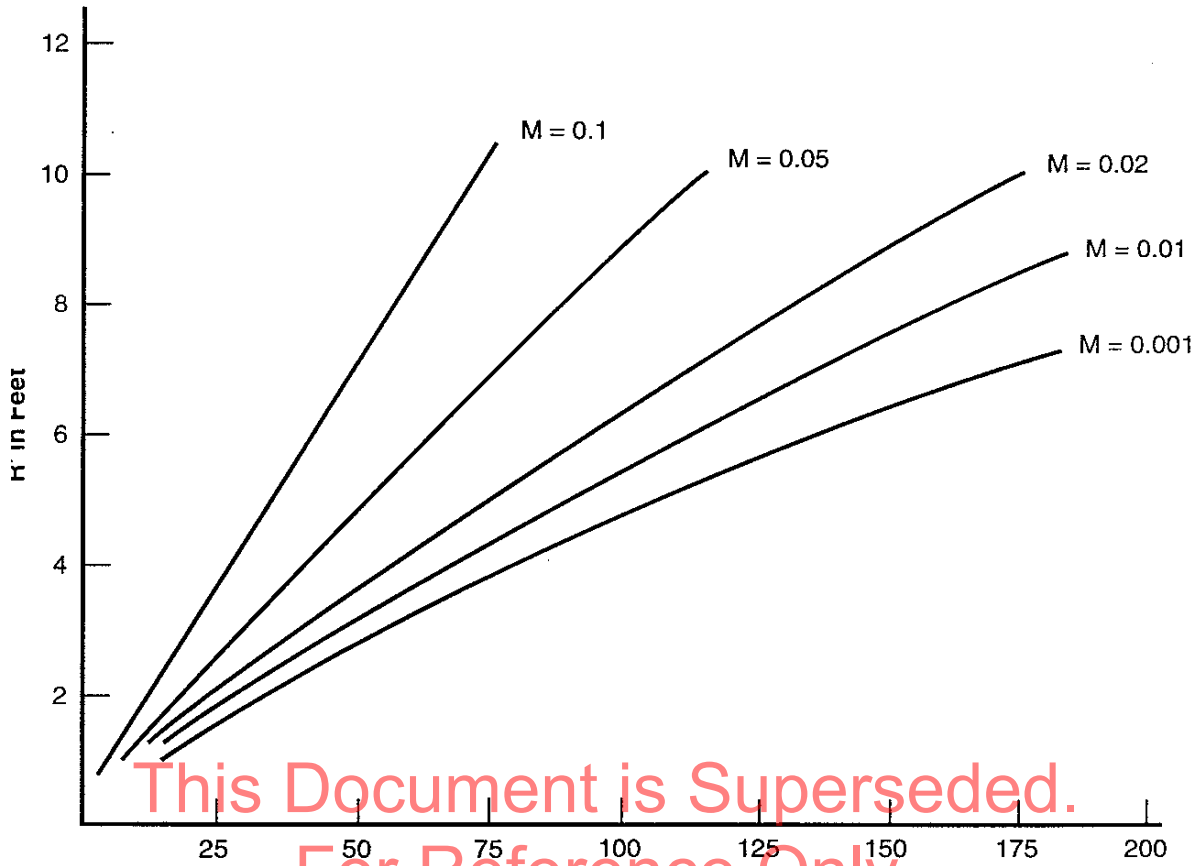


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**Figure D-17. Curves for Computation of Runup Inland of Low Bluffs**

These runup assessment procedures are given for general guidance, but situations may exist where they are not entirely applicable. For example, runup elevations need to be fully consistent with wave setup and wave overtopping assessments described in subsections that follow. In problematic cases, the Mapping Partner shall use good judgment and rely on the historical data to reach a solution about realistic flood hazards associated with a shore barrier. Subsection D.2.7 considers the integration of separately calculated wave effects into coherent hazard zonations for the 1-percent-annual-chance flood. When a unique situation is encountered, the Mapping Partner shall prepare a Special Problem Report and discuss it with the FEMA RPO.

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### D.2.5.6 Wave Setup

Nearshore wave action can increase mean water elevation in front of a shore barrier by the phenomenon called wave setup, which is related to wave attenuation by breaking in shallow water. In treating the 1-percent-annual-chance flood, focus may be restricted to the cumulative setup effect in the immediate vicinity of the shore barrier. Laboratory measurements of wave runup generally include the contribution due to wave setup, because runup elevations are defined relative to stillwater level in the absence of wave action.

A separate calculation for wave setup can be appropriate even if a wave runup elevation has already been determined, in part because the changed mean water depth can increase wave heights and crest elevations to be expected near the shore. In addition, empirical guidance within the Wave Runup Model is based on uniform laboratory wave action, so that incorporated setup might pertain to the field situation of swell waves from distant storms; setup effects may be much different in the local storm waves accompanying the 1-percent-annual-chance flood. If storm wave setup is found to exceed the wave runup calculated for a particular situation, the Mapping Partner shall apply the setup estimate as a lower bound for actual wave runup in further analysis of wave effects and 1-percent-annual-chance flood elevations.

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The USACE *Shore Protection Manual* provides straightforward empirical guidance on wave setup for various storm wave conditions and plane bottom slopes, as reproduced in Figure D-18 (USACE, 1984). Setup magnitude is given in dimensionless form, as normalized by incident significant wave height. This guidance, given typical significant storm-wave steepness of 0.03 to 0.04, indicates shore setups of 7 to 8 percent of incident wave height. Incident wave conditions are specified in deep water as the significant wave height and the wave steepness, $H_{os}/L_{op}$), where $L_p = gT_{op}^2 / 2\pi 5$ is wavelength in deep water. Bottom slope may be taken as an overall average over the breaker zone between $d = 2H_o$ and $d$=0, if the bottom geometry is relatively simple. For other geometries, e.g., with a berm or reef in front of the shore barrier, the wave setup can be larger than given by Figure 18 and a more detailed examination may be required.

Wave setup also appears appreciably larger according to an independent treatment of storm waves on plane slopes, as outlined for a relatively narrow spectrum describing incident wave energy in *Random Seas and Design of Maritime Structures* (Goda, 1985). If historical evidence indicates greater setup increases of mean water depth in extreme floods than Figure D-18 gives

for the study site, the Mapping Partner shall develop a wave setup estimate based on that independent guidance through the ACES computer program provided in *Automated Coastal Engineering System, Version 1.07* (Leenknecht, Szuwalski, & Sherlock, 1992). The program does not permit direct calculation of wave effects at d=0; however, the Mapping Partner may linearly extrapolate setup results from about $d=H_o$ to the shallow limit of computations to the stillwater shoreline.

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### D.2.5.7 Wave Overtopping

Wave overtopping results when a shore barrier does not contain incident wave action, so that floodwater penetrates to the protected area landward. This process of a partial halt and dissipation to storm waves is more difficult to treat than wave runup or wave setup. Important rates of wave overtopping can vary over several orders of magnitude, and can depend strongly on the detailed geometry of the barrier. That complicates the development of empirical guidance on wave overtopping, but little demand exists for such guidance in coastal engineering practice. According to *Criteria for Evaluating Coastal Flood-Protection Structures*, the design process for a major coastal flood protection structure relies on site-specific model testing, rather than generalized overtopping guidance (Walton, Ahrens, Truitt, & Dean, 1989).

Of course, the assessment of potential wave overtopping for present purposes must rely on readily available empirical guidance, historical effects, and engineering judgment. Except for very heavy overtopping, useful guidance is derived from tests with irregular waves, because the intermittently large overtopping discharges in storm situations could not be reproduced otherwise. Adding to the formal complexity of an adequate treatment for flood hazard assessment, overtopping effects may be cumulative so that the entire course of a flood event could require consideration, not just the peak conditions. However, the Mapping Partner shall estimate only the order of magnitude of overtopping rates because there are clearly documented thresholds below which wave overtopping may be classified as negligible. On the other hand, if a preliminary estimate indicates severe overtopping that threatens the stability of a given structure, that structure might be removed from the transect for analyses of the 1-percent-annual-chance flood, and no further overtopping consideration would be required.

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Two publications, *Design of Seawalls Allowing for Wave Overtopping* (Owen, 1980) and *Random Seas and Maritime Structures* (Goda, 1985) appear to provide the most trustworthy and wide-ranging summaries of mean overtopping rates with storm waves. The former publication addresses smooth plane or bermed slopes, and the latter publication considers vertical walls with or without a fronting rubble mound. Before surveying those primary sources of overtopping guidance, however, some introductory considerations can help to determine whether detailed assessment is needed for 1-percent-annual-chance flood conditions at a specific shore barrier.

The initial consideration is an interpretation of mean runup elevation already calculated ($\overline{R}$ 6), in terms of likely extreme elevations according to the Rayleigh probability distribution usually appropriate for wave runups. To parallel the extreme wave height addressed in coastal studies (NAS, 1977), a controlling runup magnitude may be defined as 1.6 times significant runup, or

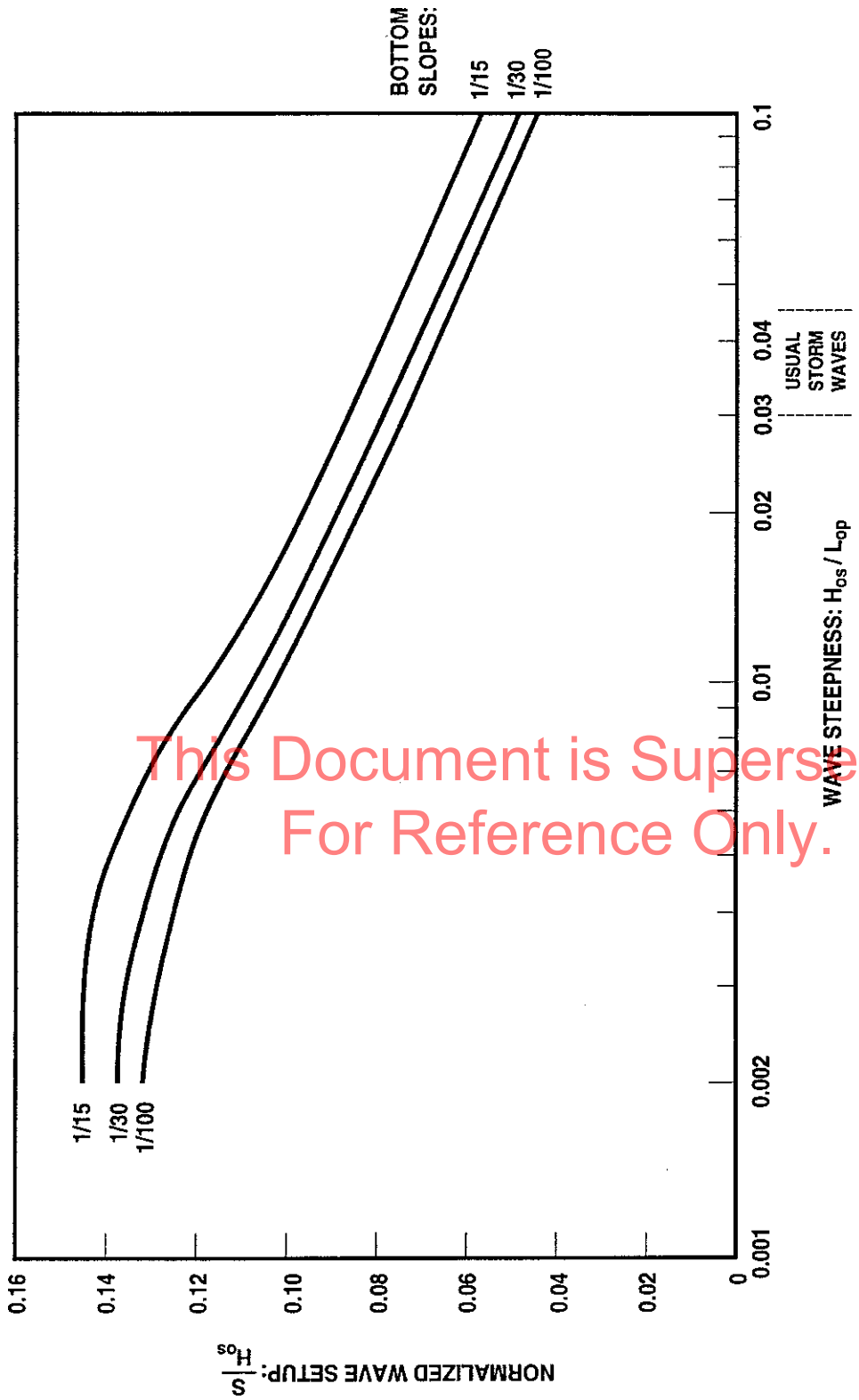


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**Figure D-18. Guidance on Wave Setup in Irregular Wave Action, From Shore Protection Manual (USACE, 1984)**

2.5 times mean runup according to the Rayleigh distribution. If elevation of the barrier crest above 1-percent-annual-chance SWEL, or the barrier freeboard $F$, equals or exceeds (2.5 $\overline{R}$ 7), then the landward area is not subject to wave-induced discharges during the 1-percent-annual-chance flood. That requirement might be supplemented by consideration of $F$ near (2 $\overline{R}$ 8), corresponding to 4.5 percent of the runup reaching the barrier crest according to the Rayleigh distribution. If $F \leq (2\overline{R}\,9)$, wave overtopping can certainly be appreciable during the 1-percent-annual-chance flood, and the Mapping Partner shall assess ponding or runoff behind the barrier. The extreme runups introduced here, ($2\overline{R}$ 10) and ($2.5\overline{R}$ 11), bracket the elevation exceeded by the extreme 2 percent of wave runup, a value commonly considered in structure design.

Once the need for quantitative overtopping assessment is established, wave runup considerations become inapplicable because a runup elevation generally cannot be converted to an overtopping estimate. Also, the composite-slope method used in determining wave runup does not appear applicable for overtopping of barriers with composite geometry, because details of the wave transformation on a barrier influence the resultant overtopping rates. Wave overtopping estimates for a specified situation generally must be based on measurements in a similar configuration. Before considering some implications of quantitative guidance for idealized cases, an overview of overtopping magnitudes gives a useful introduction (Goda, 1985; Gadd, Potter, Safaie, & Resio, 1984).

Wave overtopping is specified as a mean discharge: water volume per unit time and per unit alongshore length of the barrier, commonly cfs/ft. By interpreting or visualizing a given overtopping rate, the Mapping Partner may take into account that the actual discharges generally are intermittent and isolated, being confined to some portion of occasional wave crests at scattered locations. Distinct regimes of wave overtopping may be described as spray, splash, runup wedge, and waveform transmission, in order of increasing intensity. Flood discharges corresponding to those regimes naturally depend on the incident wave size, but certain overtopping rates have been associated with various characteristics (Goda, 1985). Among those rates, 0.01 cfs/ft seems to correspond to flooding that generally should be considered appreciable, and 1 cfs/ft appears to define an approximate threshold where structural stability of the shore barrier commonly becomes threatened by severe overtopping.

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Once the mean overtopping rate has been estimated for the 1-percent-annual-chance flood, determining resultant flooding may require a representative duration for the interval of overtopping. That duration can vary widely depending on the coastal flood cause, from a fast-moving hurricane to a nearly stationary extratropical storm. A minimum assumption for the duration of flood-peak overtopping would generally be 1 to 2 hours. Durations of 10 hours or more could be appropriate for cumulative effects in an extratropical storm causing flooding over multiple high tides.

Figure D-19 summarizes some empirical overtopping guidance for storm waves, in a schematic form meant to assist deciding the likely significance of flooding behind a coastal structure. Variables describing the basic situation are cotangent of the front slope for a smooth structure with ideally simple geometry, and freeboard of the structure crest above stillwater level, as

normalized by incident significant wave height, $F/H_s$. The mean overtopping rate, $\overline{Q}$12, is provided in dimensionless form as

$$Q^* = \overline{Q}\,13/(gH_s^3)^{0.5} \tag{2}$$

with test results shown for structure slopes of 1:1, 1:2, and 1:4 (Owen, 1980) and for a smooth vertical wall (Goda, 1985). These results pertain to: significant wave steepness of approximately $2\pi H_s/gT_p^2$ = 0.035, fairly appropriate for extreme extratropical storms or hurricanes; water depth near the structure toe of approximately $d_t = 2H_s$, so that incident waves are not appreciably attenuated; and moderate approach slopes of 1:30 for a vertical wall or 1:20 for other structures. The major feature of interpolated curves is fixed as a maximum in overtopping rate for structure slope of 1:2, corresponding to the gentlest incline producing (at this wave steepness) total reflection rather than breaking, and thus peak waveform elevations (Nagai & Takada, 1972).

These measured results for smooth and simple geometries clearly show severe or "green water" overtopping even at relatively high structures ($F \geq H_s$) for a wide range of common inclinations (cotangents between 0 and 4). Also, for freeboards considered here, a vertical wall (cotangent 0) permits less overtopping than common sloping structures with cotangent less than approximately 3.5. Gentler barriers are uncommon because the construction volume increases with the cotangent squared, so steep coastal flood-protection structures usually face attenuated storm waves and/or have rough surfaces. Basic effects of those differences can be outlined for use in simplified overtopping assessments.

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For sloping structures sited within the surf zone ($d_t < 2H_s$), *Design of Seawalls Allowing for Wave Overtopping* indicates that basic overtopping guidance in Figure D-19 can be used with attenuated rather than incoming wave height (Owen, 1980). A simple estimate basically consistent with other analyses of the 1-percent-annual-chance flood is that significant wave height is limited to $H'_s = d_t/2$ at the structure toe. The value of $(2F/d_t)$ describes the effectively increased freeboard in entering Figure D-19, and the indicated Q* value is then converted to $\overline{Q}$ using $H'_s$. The presumed wave attenuation ignores any wave setup as a small effect with the partial barrier, and $d_t$ should always correspond to the scour condition expected in wave action accompanying the 1-percent-annual-chance flood.

Figure D-19 might also be made applicable to rough slopes, using a roughness coefficient ($r$) from Table D-3 to describe the effectively increased freeboard with greater wave dissipation on the structure. *Design of Seawalls Allowing for Wave Overtopping* proposed formulating effect of structure roughness as $F/r$, and *Beach and Dune Erosion during Storm Surges* confirmed a similar dependence of overtopping on roughness in measured results for irregular waves (Owen,

1980; Vellinga, 1986). The overtopping relation reported as reliable in "Wave Runup and Overtopping on Coastal Structures" is

$$Q^* = 8 \bullet 10^{-5} \exp[3.1(rR^* - F / H_s)] \quad (3)$$

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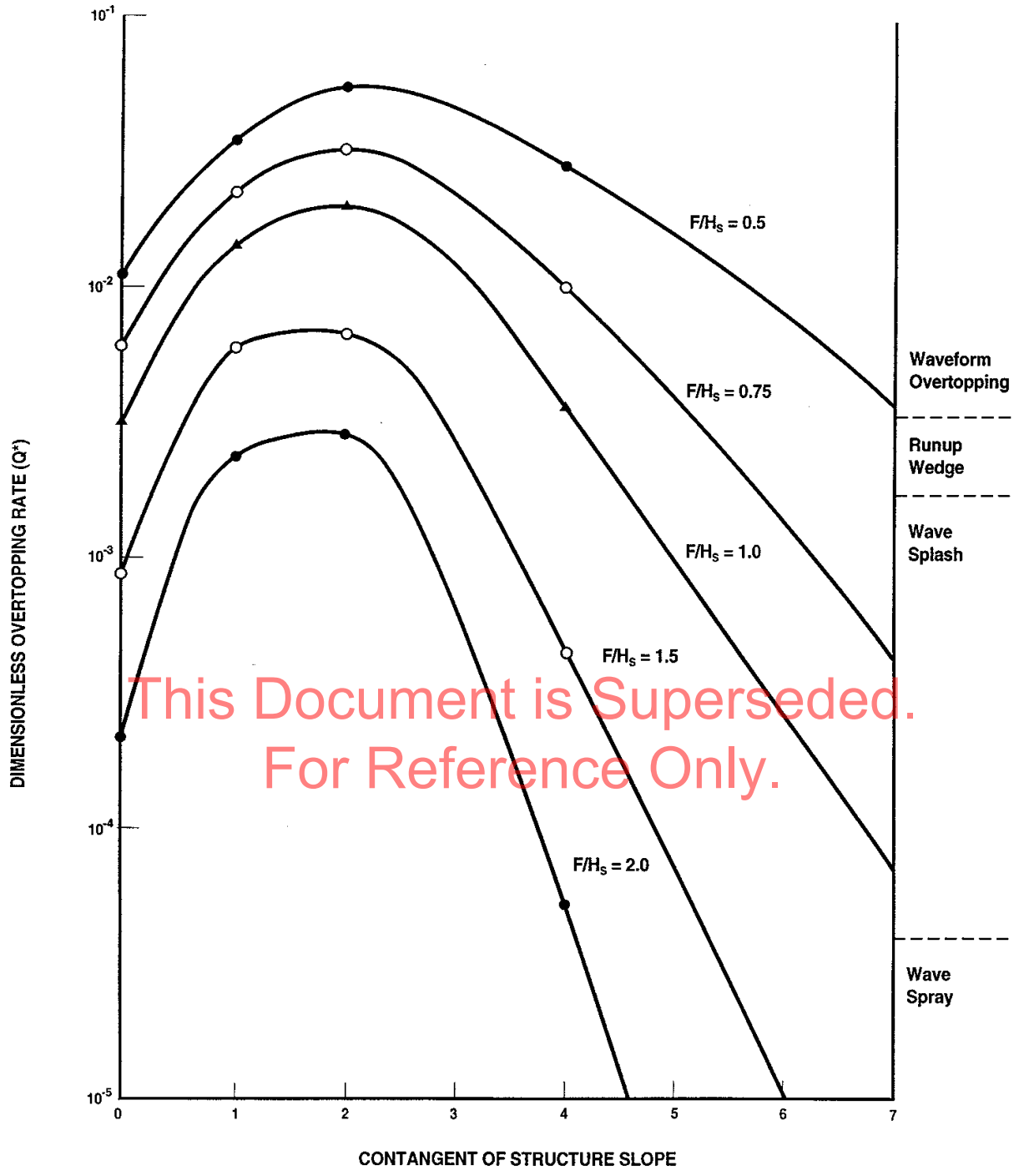


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**Figure D-19. Schematic Summary of Storm-Wave Overtopping at Structures of Various Slopes and Freeboards, Based on Goda, 1985, and Owen, June 1980.**

where $R_* = [1.5\ m/(H_s/L_{op})^{0.5}]$, up to a maximum value of 3.0, is an estimated extreme runup normalized by $H_s$, for a barrier slope given as the tangent $m$ (de Waal & van der Meer, 1992). Equation 3 is meant to pertain to very wide ranges of test situations with moderate overtopping, but appears very approximate in comparison with specific results for $r$=1 shown in Figure D-19. It may be advisable to evaluate Equation 3 for both smooth and rough barriers, then to use the ratio to adapt a value from Figure D-19 for the case with roughness. *Design of Seawalls Allowing for Wave Overtopping* (Owen, 1980) and "Wave Runup and Overtopping on Coastal Structures" (de Waal & van der Meer, 1992) provide further overtopping guidance on the effects of composite profiles, oblique waves, and shallow water with sloping structures.

For overtopping of vertical walls, effects of wave attenuation appear relatively complex, but *Random Seas and Design of Maritime Structures* (Goda, 1985) provides extensive empirical guidance on various structure situations with incident waves specified for deep water. Figure D-20 converts basic design diagrams for wave overtopping rate at a vertical wall, to display wall freeboard required for rates of 1 cfs/ft and 0.01 cfs/ft with various incident wave heights. Goda (1985) also provides a convenient summary on the effect of appreciable fronting roughness in storm waves: the required freeboard of a smooth vertical wall for a given overtopping rate is approximately 1.5 times that which is needed when a sizable mound having concrete block armor is installed against the wall. With this information, a specific vertical wall can be categorized as having only modest overtopping ($\overline{Q}14 < 0.01$ cfs/ft), intermediate overtopping, or severe overtopping ($\overline{Q}15 > 1$ cfs/ft) expected for the 1-percent-annual-chance flood. Likely runoff or ponding behind the wall must then be identified; severe overtopping requires delineation of the landward area susceptible to wave action and velocity hazard. Subsection D.2.7 outlines several common zonations of flood hazards near shore barriers in describing the integration of computed wave effects.

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Considering Figure D-20 with respect to common wall and wave heights, wave overtopping dangerous to structural stability appears the usual case during the 1-percent-annual-chance flood.

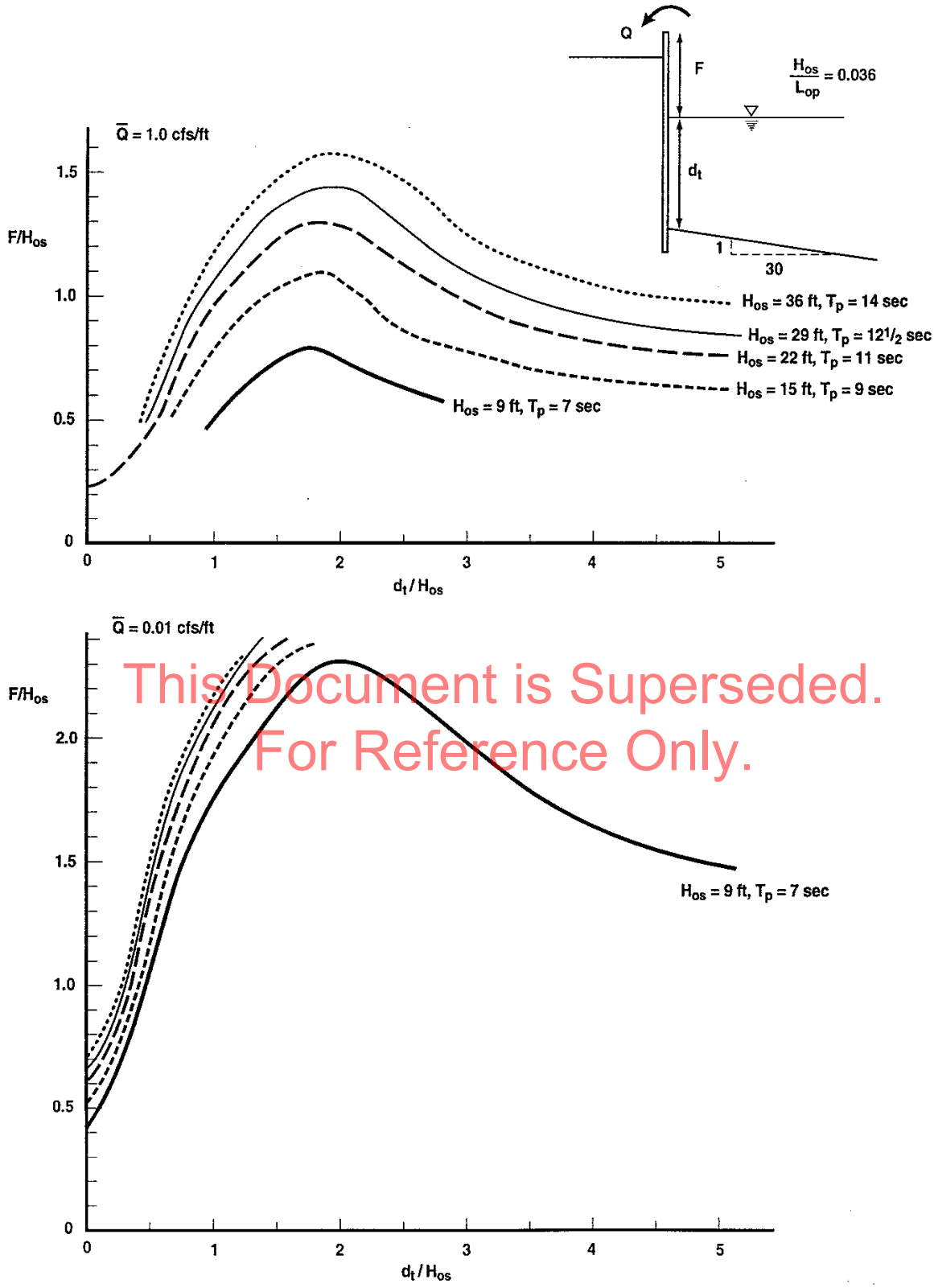


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**Figure D-20. Required Freeboard of Vertical Wall to Limit Mean Overtopping Rate to Certain Values, Based on Design Curves of *Random Seas and Design of Maritime Structures* (Goda, 1985)**

An assessment of failure during the 1-percent-annual-chance flood for typical walls would be fully consistent with one recommendation of *Criteria for Evaluating Coastal Flood-Protection Structures*: that "FEMA not consider anchored bulkheads for flood-protection credit because of extensive failures" (Walton et al., 1989).

Interpretation of estimated overtopping rate in terms of flood hazards is complicated by the projected duration of wave effects, by the increased discharge possible under storm winds, by the varying inland extent of water effects, and by the specific topography and drainage landward of the barrier. However, guidance is provided in Table D-7 as potentially applicable to typical coastal situations.

**Table D-7. Suggestions for Interpretation of Mean Wave Overtopping Rates**

| $\overline{Q}$16 ORDER OF MAGNITUDE | FLOOD HAZARD ZONE BEHIND BARRIER |
|---|---|
| <0.0001 cfs/ft | Zone X |
| 0.0001-0.01 cfs/ft | Zone AO (1 ft depth) |
| 0.01-0.1 cfs/ft | Zone AO (2 ft depth) |
| 0.1-1.0 cfs/ft | Zone AO (3 ft depth) |
| >1.0 cfs/ft* | 30-ft width+ of Zone VE (elevation 3 ft above barrier crest), landward Zone AO (3 ft depth) |

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*With estimated $\overline{Q}$17 much greater than 1 cfs/ft, removal of barrier from transect representation may be appropriate.

+Appropriate inland extent of velocity hazards should take into account structure width, incident wave period or wavelength, and other factors.

For each coastal structure experiencing sizable wave runup in the 1-percent-annual-chance flood (for example, $\overline{R}$18 > 2 ft), a brief report to the Project Officer should outline overtopping assessments and document conclusions consistent with historical evidence for the site.

[February 2002]

## D.2.6 Analysis of Overland Wave Dimensions

As water waves propagate near the shore and over flooded land, they can undergo marked transformations due to local winds, interaction with the bottom, and physical features such as buildings, trees, or marsh grass. Figure D-21 illustrates schematic effects on the wave crest elevations and on the type of flood zone. The fundamental analysis of wave effects for an FIS is provided by the WHAFIS 3.0 computer program, entitled "Wave Height Analysis for Flood Insurance Studies" (FEMA, 1988). This program or model calculates wave heights, wave crest elevations, flood hazard zone designations, and the location of zone boundaries along a transect.

Wave description for NFIP purposes addresses the controlling wave height, equal to 1.6 times the significant wave height common as a representative wave description. Significant wave

height is the average height of the highest one-third of waves, and controlling wave height is approximately the average height of the highest one percent of waves in storm conditions. The original basis for wave treatment under the NFIP was the NAS methodology, which accounted for varying fetch lengths, barriers to wave transmission, and the regeneration of waves over flooded land areas (USACE, 1975). Because of the introduction of the NAS methodology, periodic upgrades have been made to incorporate improved or additional wave considerations.

Technical details of the current WHAFIS model are fully documented *(Technical Documentation for WHAFIS Program Version 3.0*), but a brief overview indicates the level of wave treatment in WHAFIS 3.0 (FEMA, September 1988). A wave action conservation equation governs wave regeneration due to wind and wave dissipation by marsh plants. This equation is supplemented by the conservation of waves equation, which expresses the spatial variation of the wave period at the peak of the wave spectrum. The wave energy (equivalently, wave height) and wave period respond to changes in wind conditions, water depths, and obstructions as a wave propagates. These equations are solved as a function of distance along the transect. A predominant element in this wave treatment remains unchanged from the NAS methodology: controlling wave height is limited to 78 percent of the local mean water depth.

[February 2002]

### D.2.6.1 Use of WHAFIS 3.0 Model

Careful preparation and input of required site data are necessary in using WHAFIS. Like the other coastal treatments, the WHAFIS model considers the study area by representative transects. For WHAFIS, transects are selected with consideration given to major topographic, vegetative, and cultural features. The ground profile is defined by elevations referenced to NGVD and usually begins at elevation 0.0 and proceeds landward until either the ground elevation exceeds the meanwater elevation for the 1-percent-annual-chance flood or another flooding source is encountered.

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Other fundamental specifications among WHAFIS input include the 1-percent-annual-chance mean water elevation and a description of waves existing at the transect start. In the wave description, provision is made for an overwater fetch length, an initial significant wave height, or an initial period of dominant waves. In most applications, the wave period is the input description, because that parameter is readily available from information about offshore storm waves and the period does not change during most wave transformations. WHAFIS then computes an appropriate depth-limited wave height at the transect start. The only check necessary is to confirm that incident waves likely exceed that height and a wave condition limited by water depth occurs.

Different wave specifications can be appropriate for sites not on an open, straight coast. Where land shelter or wave refraction may result in reduced incident waves, it is appropriate to specify an initial significant wave height for the transect. Also, at sites on restricted water bodies, the overwater fetch length should be specified for likely wind direction at the flood peak. WHAFIS then computes an appropriate incident wave condition for the transect, but such waves are limited and any fetch length exceeding 24 miles yield the same results.

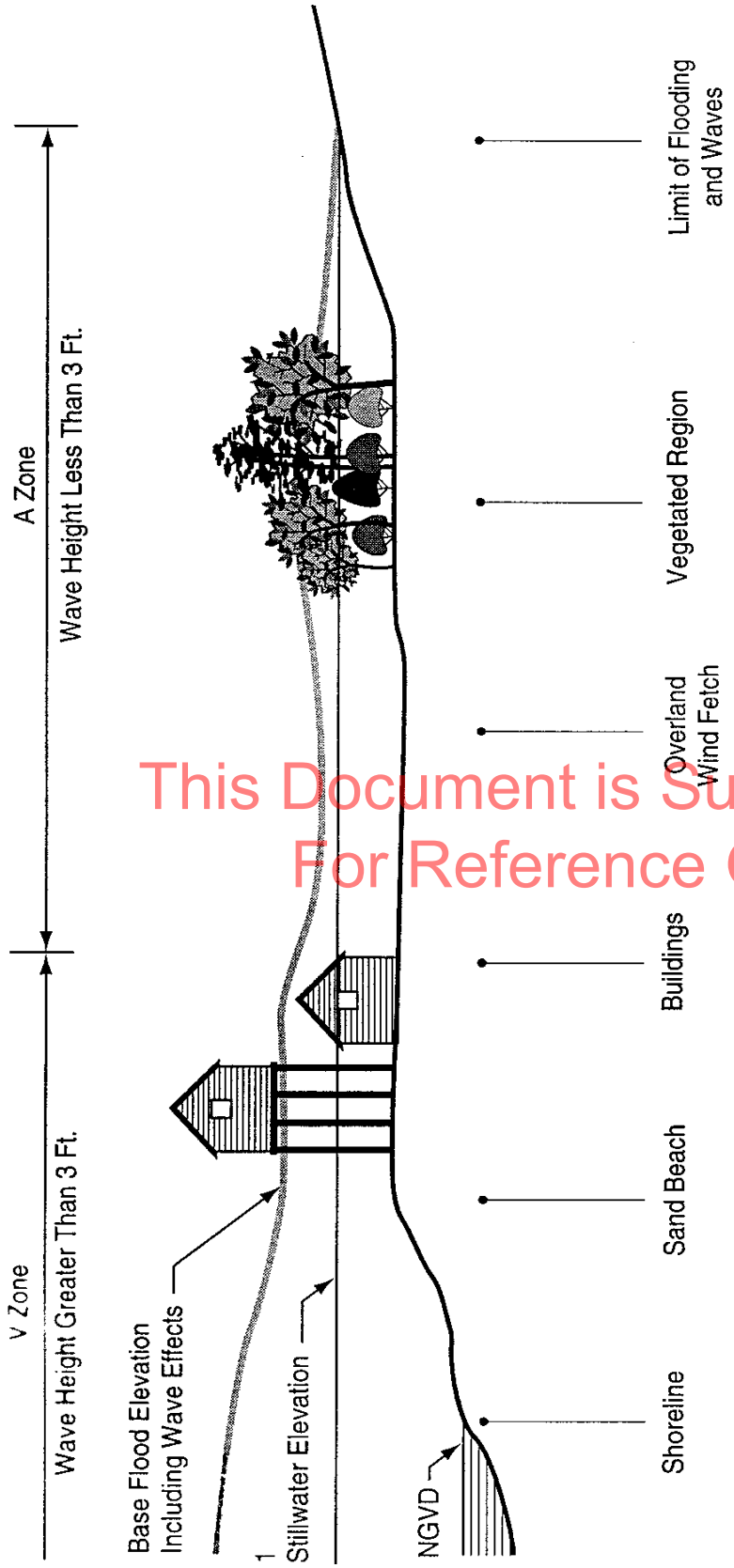


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**Figure D-21. Schematic Wave Effects on a Transect**

In preparing WHAFIS input, transects are to be located on the work maps and the transect ground profile is to be plotted from the topographic data, adjusted for erosion. Each transect is to have all the input data identified on the profile plot for ease of input coding. The location, height, and extent of elongated manmade structures is to be identified and shown as part of the ground profile, after the structure's stability under forces of the 1-percent-annual-chance flood is confirmed as discussed in Subsection D.2.3. When locating transects across barrier islands or sand spits, common practice is to continue the transect across the back bay and onto the mainland. If there is a large and/or unusually shaped embayment behind the island, it may be necessary to place additional transects just along the mainland shore. These transects may not parallel the transects from the open coast, and they may cross one another. The Mapping Partner shall keep crossing transects to a minimum; however, where it is not possible to avoid this, the transect determining greatest flood hazards shall control in mapping the flood hazards.

Once representative transects are located, the local 1-percent-annual-chance mean water levels can be defined for WHAFIS input. Wave setup should be included in this water elevation, as a part of the appropriate mean depth controlling wave dimensions (FEMA, September 1988). If wave setup was not calculated separately for the site, 1-percent-annual-chance SWEL is the appropriate specification. WHAFIS also has an input field for a 10-percent-annual-chance SWEL; however, it is only employed to determine Flood Hazard Factors, which FEMA no longer uses. Still, the Mapping Partner shall provide this input if it is readily available, because it could help in distinguishing between transects.

When a transect covers two or more flooding sources, the Mapping Partner shall identify an area of transition between the different SWELs. This is a common situation for barrier islands with ocean elevations on one side and bay elevations on the other side. It is usually assumed that the higher ocean elevations extend inland to the highest point of the reduced ground profile. WHAFIS performs a linear interpolation within a transect segment where elevations differ at the end stations. The interpolated elevations are compared to the ground elevations and adjusted, if necessary, to be above the ground elevations. The Mapping Partner may have to input the SWEL a second time to identify areas of constant elevation and elevation transition.

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The proper transect representation of some land features, particularly buildings and vegetation, merits further discussion. Buildings are specified on the transect as rows perpendicular to the transect. Because buildings are not always situated in perfect rows, the Mapping Partner shall exercise judgment to determine which buildings can be represented by a single row. The required input value for each row of buildings is the ratio of open space to total space. This is simply the sum of distances between buildings in a row, divided by the total length of that row. The Mapping Partner shall examine whether the first row or two of buildings along the shoreline should be considered as obstructions. During a 1-percent-annual-chance event, it is sometimes appropriate to assume that these buildings will be destroyed before the peak of the flood occurs if they are not elevated on pilings. If they are elevated, the waves should propagate under the structure with minimal reduction in height. It is useful to contact local officials to obtain typical construction methods and the lowest elevations of structures.

The WHAFIS program has two separate routines for vegetation: one for rigid vegetation that can be represented by an equivalent "stand" of equally spaced circular cylinders (NAS, 1977),

and one for marsh vegetation that is flexible and oscillates with wave action (FEMA, 1984). For either type, the Mapping Partner shall exercise considerable care in selecting representative parameters and in ruling out that the vegetation will be intentionally removed or that effects would be markedly reduced during a storm through erosion, uprooting, or breakage.

For the areas of rigid vegetation located on the transect, the required input values are the drag coefficient, $C_D$; mean wetted height, h; mean effective diameter, D; and mean horizontal spacing, b. The value of $C_D$ should vary between 0.35 and 1.0, with 1.0 being used in most cases of wide vegetated areas. When the vegetation is in a single stand, the Mapping Partner shall use a value of 0.35. The Mapping Partner may obtain representative values for h, D, and b from stereoscopic aerial photographs or by field surveys. Various guides for terrain analysis can provide advice on estimating values from aerial photographs. Table D-8 provides a useful process developed from *Terrain Analysis Procedural Guide for Vegetation* (Messmore, Vogel, & Pearson, 1979).

For marsh vegetation, a more complicated specification is required for completeness. The eight parameters used to describe the dissipational properties of a specific type are explained in Table D-9. However, WHAFIS incorporates considerable basic information on the eight common types of seacoast marsh plants listed in Table D-10 (FEMA, 1984). That information can be used either by specifying the Table D-10 abbreviation or a geographical region as indicated in Figure D-22. Figure D-22 shows the coastal wetland regions of the Atlantic and Gulf coasts, along with the identifying number used in WHAFIS. If the site is near a region border, the likely plant parameters can be interpolated using an input weighting factor. Although the South Texas region has insignificant amounts of marsh grass, it is included for usage in spatial interpolation.

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Climate affects the geographic range of each marsh plant type, so that some plant types are not found in all regions. Table D-11 lists the dominant plant type in each region, where the term "dominant" refers to the plant types that cover the largest amount of area in the marshes. Table D-12 shows the significant plant types in each region, where the term "significant" refers to the plant types that occur in large enough patches (at least 10,000 square feet) to significantly affect waves. For marsh plants, simply the coastal wetland region, plant type, and area or percent of coverage may be specified. Given this information, WHAFIS will supply default values for the other marsh plant parameters appropriate to the site (FEMA, 1984).

Following the identification of the marsh plant types present, the area and fraction of coverage, $F_{cov}$, for each plant type must be calculated. For each transect, the total area of marsh vegetation coverage is determined. The different types of vegetation within this area usually occur in patches. $F_{cov}$ is defined for each plant type as the ratio of the patch area for that type to the total marsh area. Using the above data, a fairly good determination can be made of the plant types present, but an attempt should be made to confirm these plant types. Local, county, or state officials may provide some assistance, and a site visit can be very useful.

Table 8.

Procedures for Vegetation Analysis

Using Stereoscopic Aerial Photographs

1. Using the parallax bar or wedge, determine the height of three representative trees and compute the average height, h.

2. Locate three representative tree crowns, measure the diameters, and compute the average crown diameter, CD.

3. Determine the type of vegetation and calculate the stem diameter, D, using the following formulae:

| | |
|---|---|
| Southern Pines | D (inches) = 5 + 0.5 CD (feet) |
| Eastern Hardwoods, Northern Pines and Others | D (inches) = 0.75 CD (feet) |

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4. Based on the scale of the aerial photographs, determine the diameter of a circle containing 0.08 hectares using Table 8a. Place the circle on the photograph, over a representative area of trees, and count the number of trees, n, in the circle. A magnifier may be needed. More than one area can be counted and an average used for n. Calculate the number of trees per hectare, N, using the following formula:

$$N = \frac{n}{0.08}$$

5. Determine the horizontal spacing between trees using the following formula:

$$b\ (feet) = (\frac{12732}{N} - \frac{D\ (inches)}{12}$$

**Table D-8. Procedures for Vegetation Analysis Using Stereoscopic Aerial Photographs (Cont.)**

CIRCLE DIAMETERS
.08 HECTARE AREA, (1/5 ACRE)
(800 Square Meters, 8712 Square Feet)

| PHOTO SCALE | .08 HECTARE CIRCLE | CIRCLE DIAMETER | |
|---|---|---|---|
| | | INCHES | MILLIMETERS |
| 1:5,000 | | .253 | 6.38 |
| 1:6,000 | | .211 | 5.32 |
| 1:7,000 | | .1805 | 4.56 |
| 1:8,000 | | .158 | 3.99 |
| 1:9,000 | | .140 | 3.55 |
| 1:10,000 | | .126 | 3.192 |
| 1:11,000 | | .115 | 2.90 |
| 1:12,000 | | .105 | 2.66 |
| 1:13,000 | | .092 | 2.46 |
| 1:14,000 | | .090 | 2.28 |
| 1:15,000 | | .084 | 2.13 |
| 1:16,000 | | .079 | 1.99 |
| 1:17,000 | | .074 | 1.88 |
| 1:18,000 | | .070 | 1.77 |
| 1:19,000 | | .067 | 1.68 |
| 1:20,000 | | .063 | 1.60 |
| 1:21,000 | | .060 | 1.52 |
| 1:22,000 | | .057 | 1.45 |
| 1:23,000 | | .055 | 1.39 |
| 1:24,000 | | .053 | 1.33 |
| 1:25,000 | | .051 | 1.28 |

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**Table D-9. Marsh Plant Parameters**

| PARAMETER | EXPLANATION |
|---|---|
| $C_D$ | Effective drag coefficient. Includes effects of plant flexure and modification of the flow velocity distribution. Default value is 0.1, usually appropriate for marsh plants without strong evidence to the contrary. |
| $F_{cov}$ | Fraction of coverage. A default value is calculated by the program so that each plant type in the transect is represented equally, and the sum of the coverage for the plant types is equal to 1.0. |
| h | Unflexed stem height (feet). The stem height does not include the flowering head of the plant, the inflorescence. |
| N | Number density. Expressed as plants per square foot. The relationship to the average spacing between plants, b, can be expressed as $N = 1/b^2$. |
| $D_1$ | Base stem diameter (inches). Default value may be determined from stem height and regression equations built into the program. |
| $D_2$ | Mid stem diameter (inches). Default value may be determined from plant type and base stem diameter. |
| $D_3$ | Top stem diameter (inches), at the base of the inflorescence. Default value may be determined from plant type and base stem diameter. |
| $CA_b$ | Ratio of the total frontal area of the cylindrical portion of the leaves to the frontal area of the stem below the inflorescence. Default value may be determined from the plant type. |

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**Table D-10. Abbreviations of Marsh Plant Types used in WHAFIS**

| SPECIES OR SUBSPECIES | ABBREVIATION |
|---|---|
| *Cladium jamaicense* (saw grass) | CLAD |
| *Distichlis spicata* (salt grass) | DIST |
| *Juncus gerardi* (black grass) | JUNM |
| *Juncus roemerianus* (black needlerush) | JUNR |
| *Spartina alterniflora* (medium saltmeadow cordgrass) | SALM |
| *Spartina alterniflora* (tall saltmeadow cordgrass) | SALT |
| *Spartina cynosuroides* (big cordgrass) | SCYN |
| *Spartina patens* (saltmeadow grass) | SPAT |

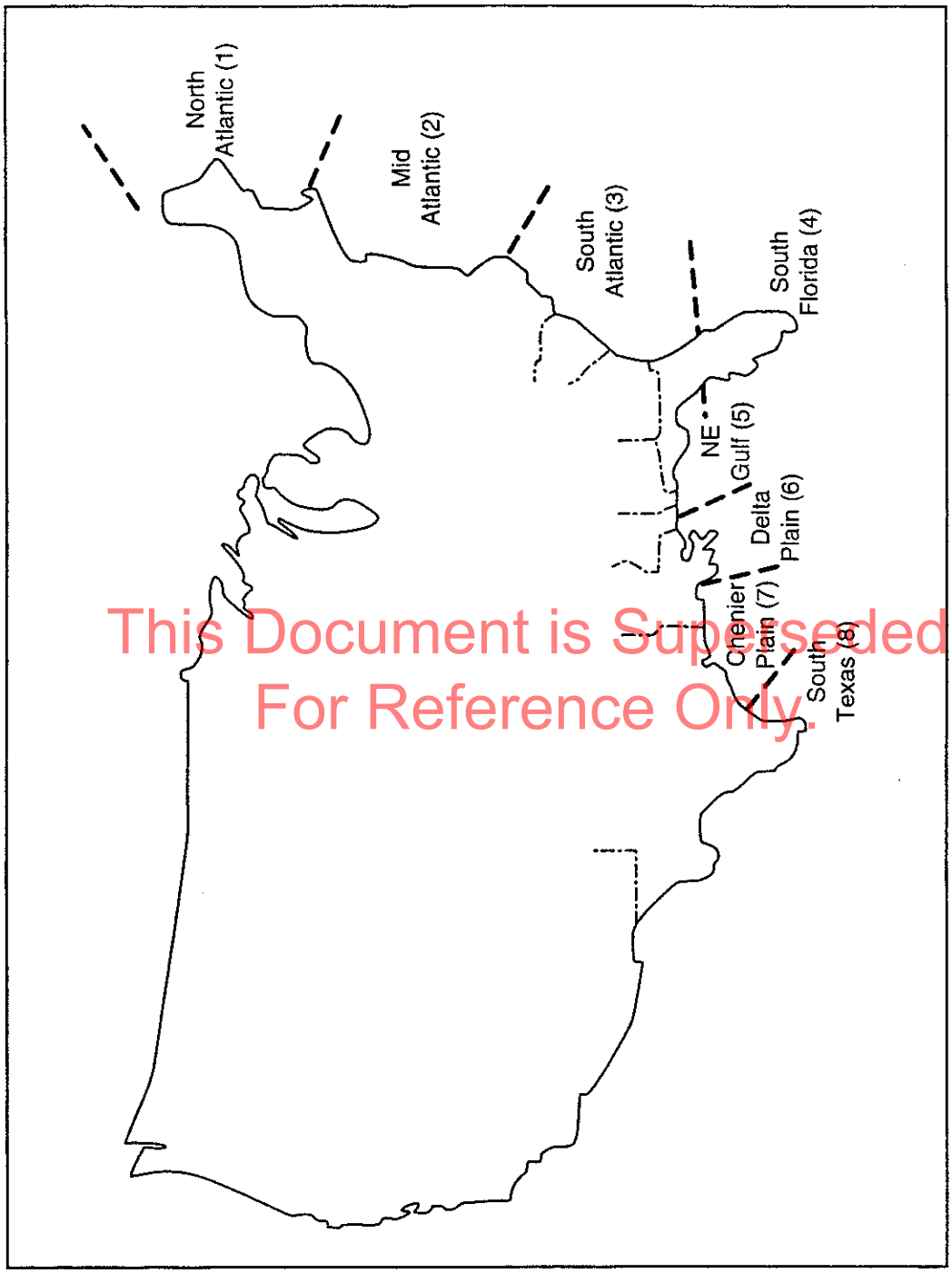


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**Figure D-22. Coastal wetland regions of Atlantic and Gulf coasts having enough marsh grass to significantly affect wave heights. Region numbers are indicated in parentheses.**

**Table D-11. Dominant Marsh Plant Types by Region and Habitat**

| REGION NUMBER | REGION NAME | HABITAT | DOMINANT SPECIES |
|---|---|---|---|
| 1 | North Atlantic | salt[1]<br>brackish[2] | **S. alterniflora* (medium, tall)<br>*Spartina patens* |
| 2 | Mid-Atlantic | salt<br>brackish | *S. alterniflora* (medium, tall)<br>**Juncus roemerianus/S. patens* |
| 3 | South Atlantic | salt<br>brackish | **S. alterniflora* (medium, tall)<br>*J. roemerianus* |
| 4 | South Florida | salt<br>brackish | *S. alterniflora* (medium, tall)<br>**C. jamaicense* |
| 5 | Northeastern Gulf | salt<br>brackish | ---<br>**J. roemerianus* |
| 6 | Delta Plain | salt<br>brackish | **S. Alterniflora* (medium, tall)<br>*S. patens* |
| 7 | Chenier Plain | salt<br>brackish | *S. alterniflora* (medium, tall)<br>**S. patens* |
| 8 | South Texas | salt<br>brackish | ---<br>--- |

[1]Salt concentration is greater than 20 parts per thousand (ppt)

[2]Salt concentration is between 5 and 20 ppt

*When more than one dominant plant type occurs within the region, the indicated type covers the largest geographic area (acreage)

--- Insignificant amounts of marsh plants within the given habitat in the region

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**Table D-12. Significant Marsh Plant Types in Each Seacoast Region and WHAFIS Default Regional Plant Parameter Data**

| REGION NO. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| REGION NAME: | NORTH ATLANTIC | MID-ATLANTIC | SOUTH ATLANTIC | SOUTH FLORIDA | NORTHEASTERN GULF | DELTA PLAIN | CHENIER PLAIN | SOUTH TEXAS |
| CLAD | --- | --- | --- | 7.50(+)<br>0.0656<br>6 | 6.00(2)<br>0.0260<br>6 | --- | --- | --- |
| DIST | --- | 0.78(1)<br>0.0039<br>211 | 1.00(1)<br>0.038<br>243 | 1.00(+)<br>0.0038<br>248 | ---<br>--- | 1.08(4)<br>0.0035<br>102 | 1.08(+)<br>0.0035<br>102 | --- |
| JUNM | 1.23(1)<br>0.0042<br>300 | 1.23(+)<br>0.0042<br>300 | --- | --- | --- | --- | --- | --- |
| JUNR | --- | 2.95(+)<br>0.0095<br>147 | 2.95(+)<br>0.0095<br>147 | --- | 2.95(3)<br>0.0095<br>147 | 3.00(4)<br>0.0106<br>83 | 2.95(+)<br>0.0095<br>147 | --- |
| SALM | 1.39(1)<br>0.0184<br>45 | 1.06(1)<br>0.0103<br>36 | 1.63(1)<br>0.0141<br>12 | 1.63(+)<br>0.0141<br>12 | --- | 1.67(4)<br>0.0141<br>21 | 2.62(5)<br>0.0211<br>16 | --- |
| SALT | 1.86(1)<br>0.0175<br>37 | 2.21(1)<br>0.0169<br>18 | 3.20(1)<br>0.0183<br>10 | 3.20(+)<br>0.0183<br>10 | --- | 3.20(4)<br>0.0183<br>10 | 3.20(+)<br>0.0183<br>10 | --- |
| SCYN | --- | --- | 8.29(+)<br>0.0492<br>6 | --- | --- | 4.00(4)<br>0.0267<br>7 | --- | --- |
| SPAT | 1.03(1)<br>0.0025<br>409 | 0.85(1)<br>0.0019<br>327 | 1.65(1)<br>0.0019<br>236 | --- | 2.58(2)<br>0.0026<br>236 | 1.88(4)<br>0.0016<br>333 | 1.88(+)<br>0.0019<br>333 | --- |

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Data arranged in vertical triplets:

h, stem height below inflorescence, in feet
D, base diameter, in feet
N, number density, in inverse square feet

Parenthetical references indicate data source:

1 = Hardisky and Reimold, 1977
2 = Monte, August 1983
3 = Kruczynski, Subrahmanyam, Drake, 1978
4 = Hopkinson, Gosselink, Parrondo, 1980, Diameters extrapolated
5 = Turner and Gosselink, 1975, Diameters extrapolated
+ = Extrapolated Data
--- = Insignificant amounts of this plant type in the region

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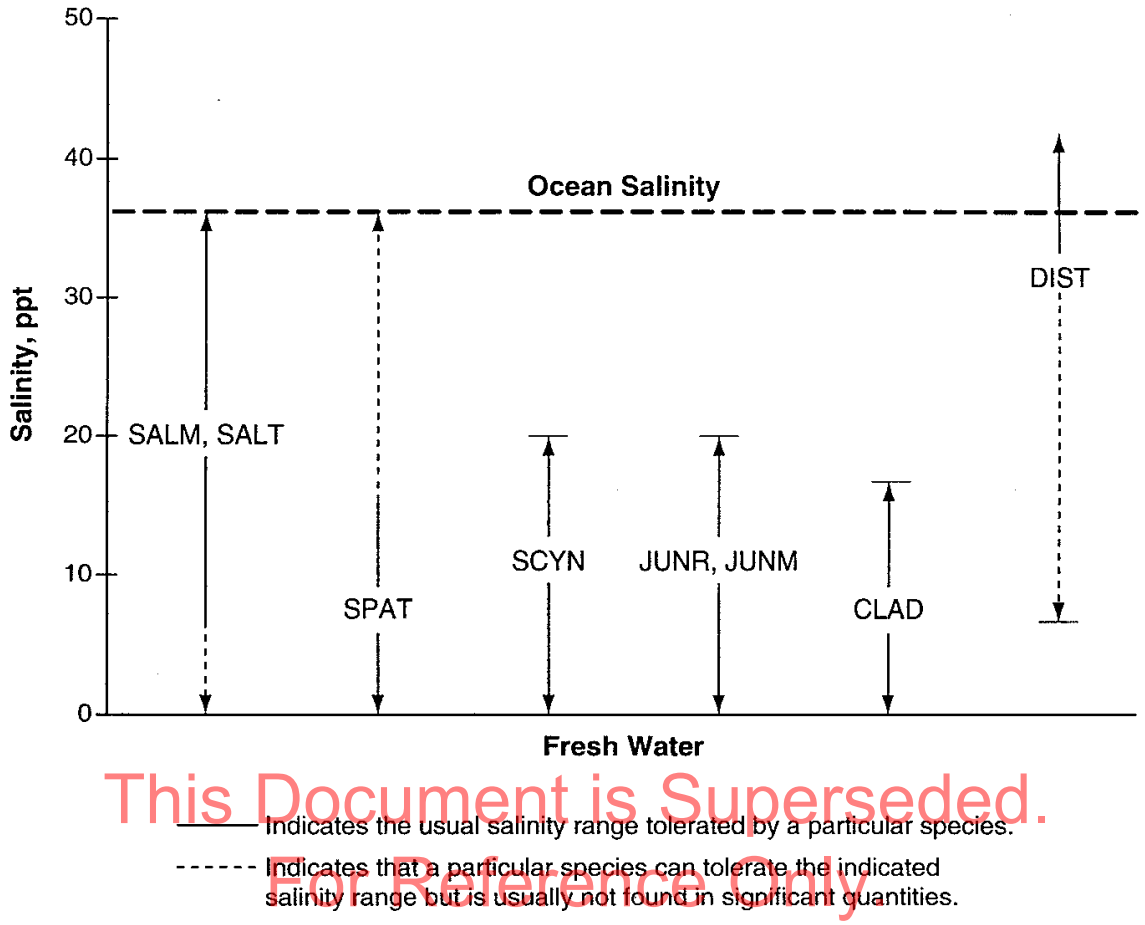


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**Figure D-23. Salinity Tolerance of Marsh Plants, from Knutson & Woodhouse, 1983**

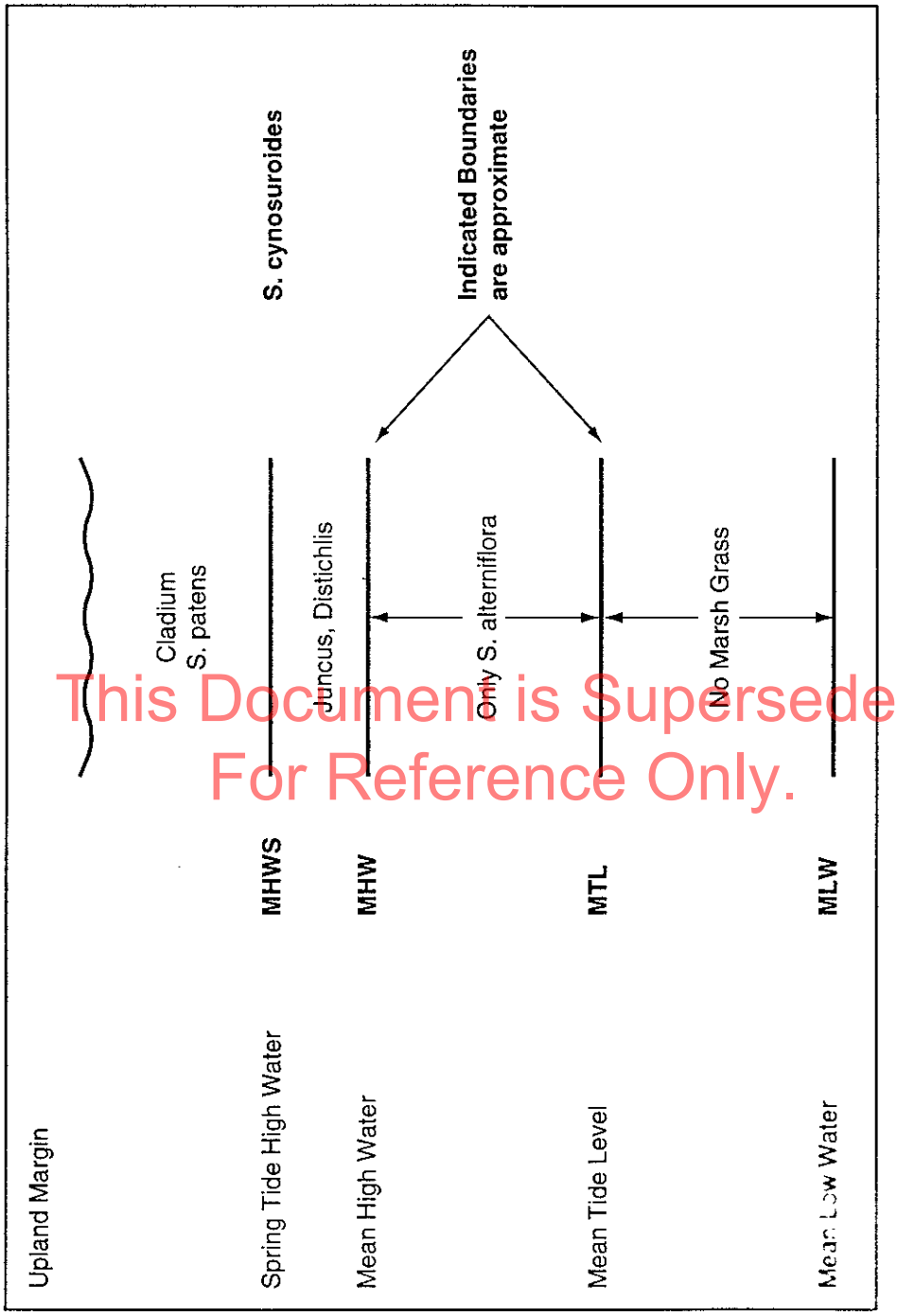


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**Figure D-24. Tidal Control on Salt Marsh Plant Viability**

### D.2.6.2 Input Coding for WHAFIS

After all the necessary input data have been identified on the transect, the Mapping Partner shall divide the transect into contiguous segments, each representing a continuous open fetch or a single obstruction. Fetches are flooded areas with no obstruction, while obstructions include dunes, manmade barriers, buildings, and vegetation. The Mapping Partner shall subdivide the fetches at points where the ground elevation abruptly changes and in the transition area of changing SWELs. The Mapping Partner shall subdivide obstructions into smaller segments at the transect's seaward edge to model the wave dissipation more accurately. Rigid vegetation shall have two to three seaward segments extending 10 to 50 feet, and the first two or three rows of buildings shall have a segment for each row. Marsh vegetation will be subdivided within WHAFIS, so segmented input from the Mapping Partner is not necessary.

The Mapping Partner shall enter the necessary data using 11 line types, including the Title line. The ten remaining lines, each describing a certain type of fetch or obstruction, are listed as follows:

- The IE (Initial Elevation) line describes the initial overwater fetch and the initial SWELs.
- The IF (Inland Fetch) and OF (Overwater Fetch) lines define the endpoint stationing and elevation of inland and overwater fetches, respectively.
- Obstructions are categorized either as buildings (BU line), rigid vegetation (VE line), marsh vegetation (VH and MG lines), dunes and other natural or manmade elongated barriers (DU line), or areas where the ground elevation is greater than the 1-percent-annual-chance SWEL (AS line).
- The ET (End of Transect) line enters no data but indicates the end of the input data.

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Each line has an alphanumeric field describing the type of input for that line, followed by ten numeric fields describing the parameters.

To ensure proper modeling, the Mapping Partner shall enter all segments of each transect either as fetches or obstructions, with one input line required for each fetch or obstruction segment. The first two columns of each line identify the type of fetch or obstruction. The remaining 78 columns consist of one field of six columns followed by nine fields of eight columns. The Mapping Partner shall right-justify the numbers in any data field only if no decimal point is used. Decimal points are permitted but not required. The end point of one fetch or obstruction is the beginning of the next. The first two numeric fields of each line are used to read in the stationing (measured in feet from the beginning of transect) and elevation (in feet) of the end point. The last two fields used on each line are for entering new SWELs. An interpolation is performed within a transect segment starting at the closest station with an input SWEL. This interpolation uses the new SWEL input at the end point of the segment and the SWEL input at a previous segment. If these fields are blank or zero, the SWELs remain unchanged.

The input data requirements are summarized below for each line type. The Title line must be the first line, followed by the IE line, followed by any combination of the various fetch and obstruction lines. The ET line must be the last card entered for the transect. A blank line must follow to signify the end of the run. If multiple transects are being run, the Title line for the next transect will follow the blank line. All units are in feet unless otherwise specified.

## TITLE Line (Title)

This line is required and must be the first input line.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | Blank |
| 1-10 | 3-80 | Title information centered about column 40 |

## IE Line (Initial Elevations)

This line is required and must be the second input line. This line is used to begin a transect at the shoreline and compute the wave height arising through the overwater fetch.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | IE |
| 1 | 3-8 | Stationing of end point of initial overwater fetch in feet (zero at beginning of transect) |
| 2 | 9-16 | Ground elevation at end point in feet (usually zero at beginning of transect) |
| 3 | 17-24 | Overwater fetch length (miles), if wave condition is to be calculated. Values of 24 miles or greater yield identical results. |
| 4 | 25-32 | 10-percent-annual-chance SWEL in feet |
| 5 | 33-40 | 1-percent-annual-chance SWEL in feet |
| 6 | 41-48 | Initial wave height in feet; a blank or zero causes a default to a calculated wave height |
| 7 | 49-56 | Initial wave period (seconds); a blank or zero causes a default to a calculated wave period. The period is usually the most convenient wave specification for open coasts. |
| 8-10 | 57-80 | Not used |

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## AS Line (Above Surge)

This line is used to identify the end point of an area with ground elevation greater than the 1-percent-annual-chance SWEL (such as a high dune or other land mass). This is used when the ground surface temporarily rises above the 1-percent-annual-chance SWEL. The line immediately preceding the AS line must enter the stationing and elevation of the point at which the ground elevation first equals the 1-percent-annual-chance SWEL. SWEL on the inland side may differ from SWEL on the seaward side. The ground elevation entered on the AS line must

equal the SWEL that applies to the inland side of the land mass. Computer calculations will be terminated if a ground elevation greater than the 1-percent-annual-chance SWEL is encountered.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | AS |
| 1 | 3-8 | Stationing at end point in feet of area above 1-percent-annual-chance SWEL |
| 2 | 9-16 | Ground elevation in feet at end point |
| 3 | 17-24 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to the 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

BU Line (Buildings)

This line enters information needed to compute wave dissipation at each group of buildings.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | BU |
| 1 | 3-8 | Stationing of end point in feet of group of buildings |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | Ratio of open space between buildings to total transverse width of developed area |
| 4 | 25-32 | Number of rows of buildings |
| 5 | 33-40 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 6 | 41-48 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 7-10 | 49-80 | Not used |

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DU Line (Dune)

This line enters information necessary to compute wave dissipation over flooded sand dunes and other natural or manmade elongated barriers (e.g., levees and seawalls).

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | DU |
| 1 | 3-8 | Stationing at top of dune or barrier in feet |
| 2 | 9-16 | Elevation at top of dune or barrier in feet |
| 3 | 17-24 | A blank or zero indicates a dune or other natural barrier; any other number indicates a seawall or other manmade barrier |
| 4 | 25-32 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 5 | 33-40 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; |

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| | | otherwise new 1-percent-annual-chance SWEL |
| 6-10 | 41-80 | Not used |

IF Line (Inland Fetch)

This line enters the parameters necessary to compute wave regeneration through somewhat sheltered fetches and over shallow inland water bodies. The IF regeneration is computed using a sustained wind speed of 60 mph.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | IF |
| 1 | 3-8 | Stationing at end point of fetch in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

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OF Line (Overwater Fetch)

This line enters the parameters necessary to compute wave regeneration over large bodies of water (i.e., large lakes, bays) using a sustained wind speed of 80 mph. If an inland body of water is sheltered and has a depth of ten feet or less, the IF line calling for reduced wind speed should be used.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | OF |
| 1 | 3-8 | Stationing at end point of fetch in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

## VE Line (Vegetation)

This line enters parameters necessary to compute wave dissipation due to rigid vegetation stands.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | VE |
| 1 | 3-8 | Stationing at end point of vegetation in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | Mean effective diameter of equivalent circular cylinder in feet |
| 4 | 25-32 | Average actual height of vegetation in feet |
| 5 | 33-40 | Average horizontal spacing between plants in feet |
| 6 | 41-48 | Drag coefficient; a blank or zero causes a default to 1.0 |
| 7 | 49-56 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 8 | 57-64 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 9-10 | 65-80 | Not used |

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## VH Line (Vegetation Header for Marsh Grass)

Marsh grass is often part of a plant community that may consist of several types. The VH line is used to enter data that apply to all plant types modeled in the transect segment. To enter data for each plant type, MG lines for each plant type must follow the VH line.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | VH |
| 1 | 3-8 | Stationing at end point of marsh vegetation segment in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | $Reg_p$, number of the primary seacoast region for default plant parameters. See Figure 22. |
| 4 | 25-32 | $Wt_p$, weighting factor for the primary seacoast region. |
| 5 | 33-40 | $Reg_s$, number of secondary seacoast region. See Figure D-22. |
| 6 | 41-48 | $N_{p1}$, number of plant types; range is 1 to 10, inclusive. One MG line is required for each plant type. |
| 7 | 49-56 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 8 | 57-64 | A blank or zero indicates no change to the 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 9 | 65-72 | Not used |
| 10 | 73-80 | This field is for overriding the default method of averaging flood hazard factors |

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| | | in A Zones; if 1 in column 80, averaging process begins or ends at end of vegetation segment; otherwise, default averaging method is used |

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MG Line (Marsh Grass)

This line is used to enter data for a particular plant type. The first MG line must be preceded by a VH line. For the common seacoast marsh grasses listed in Table D-10, some potentially useful default values are supplied in Table D-12, and the program can provide additional default values (FEMA, October 1984). If a plant type not listed in the table is used, then appropriate data must be developed for Fields 2-9.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | MG |
| 1 | 5-8 | Marsh plant type abbreviation (see Table 10) |
| 2 | 9-16 | $C_D$, effective drag Coefficient; default value is 0.1 |
| 3 | 17-24 | $F_{cov}$, decimal fraction of vegetated area to be covered by this plant type; a blank or zero causes a default to be calculated so that each plant type is represented equally |
| 4 | 25-32 | h, mean unflexed height of stem (feet); for marsh plants, the inflorescence is not included |
| 5 | 33-40 | N, number of plants per square foot |
| 6 | 41-48 | $D_1$, base stem diameter (inches) |
| 7 | 49-56 | $D_2$, mid stem diameter (inches) |
| 8 | 57-64 | $D_3$, top stem diameter (inches) |
| 9 | 65-72 | $CA_b$, ratio of the total frontal area of cylindrical part of leaves to frontal area of main stem |
| 10 | 73-80 | Not used |

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ET Line (End of Transect)

This line is required and must be the last input card because it identifies the end of input for the transect.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | ET |
| 3-10 | 3-80 | Not used |

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### D.2.6.3 Error Messages

The error messages that may appear when running the model are described below.

- "AS card ground elevation less than SWEL, should use other type card, job dumped."

  Only use AS (above surge) line when the ground elevation is above the SWEL. Can otherwise use IF, OF, BU, DU, VE, or VH.

- "Ground elevation greater than surge elevation encountered, job dumped."

If ground elevation is above surge elevation, AS card should be used.

- "Average depth less than or equal to zero, job dumped."

  The water depth must be greater than zero or a wave height cannot be computed. Check the SWEL and the ground elevation if point of job dump is not the last point along the transect profile.

- "The above card contains illegal data in the first 2 columns."

  Check input data for incorrect values or input within wrong columns. Aside from the title line, the first two columns in each line should contain the card identifiers.

- "Transmitted wave height at last fetch or obstruction = _____ which exceeds 0.5."

  Code the transect profile up to the inland limit where ground elevation intersects the SWEL so that wave height should decrease to zero. If the scope of work ends at the corporate limits before the ground elevation meets the SWEL, this message can be ignored.

- "Array dimensions exceeded. Job dumped."

  Size of the array is limited and the number of input parameters has exceeded the array. Check the number of input parameters at the location where the job dumped.

- "Invalid data in field 1 of IF card," etc.

  Check input data to make sure that data are in correct columns.

- "Wave period less than or equal to zero in subroutine fetch. Abort run."

  Either a fetch length or a wave period must be input for the program to run properly. Check input data.

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- "Invalid data in field 3 or field 5 of VH card."

  Check input data.

- "Invalid data in field 4 of VH card."

  Check input data.

- "Invalid data in field 3 of MG card."

  Check input data. The fraction of vegetated area covered by the stated plant type should be a decimal number between 0.0 and 1.0.

- "Missing MG card or incorrect data in field 6 of VH card."

  A MG card must always follow the VH card. Field 6 of the VH card pertains to the number of plant types, and one MG card is required for each plant type.

- "Invalid input data."

  Check input data for invalid characters, such as an O instead of a zero. Check to be sure that all data are in their correct columns.

- "Fcov was found to be negative for plant type = _____."

  Check input data to be sure that the decimal fraction of the vegetated area covered by the plant type is not negative.

- "Ncov is .LE. zero in Sub.Lookup when it should be .GT. zero. Abort run."

  Check input for number of plants covering the area.

- "The first card is not an IE card, this transect is aborted. Continued to next transect."

  The first card after the title line must always be an IE card. Check input data.

- "**** The surge elevation at this station (stationing ____), which is ____ card, is less than the ground elevation. The interpolation process is continued. *** Please double check the surge and ground elevations in the vicinity of this station"

  The surge elevation should not be below the ground elevation. If the interpolated surge elevation is interpolated below the ground elevation, insert additional cards to specify surge and ground elevations and use an AS card if necessary.

- "Interpolation line cuts off more than two portions of high ground ridge. This transect is aborted, re-assign 1-percent-annual-chance elevations at high ground stations."

  When the interpolated value falls below the ground elevation, insert additional cards to better model the area and set the SWEL equal to the ground elevation where appropriate. Insert AS cards as necessary.

- "**** Unreasonable high ground elevation at station ____ which is ____ card. This transect is aborted, continued to next transect. **** Double check the surge and ground elevations in the vicinity of this station. If the ground elevations are correct, either assign a higher surge elevation or use AS cards."

  Add additional input data as necessary to better define the ground elevation and surge elevation in this area.

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### D.2.6.4 Output Description

The output of the program provides all the data necessary for plotting the BFEs and flood insurance risk zones along the transect. The output is in six parts:

**Part 1 - Input**

This is a printout showing all input data lines and the parameters assigned to each line, both manually and by default. This is followed by a more detailed printout with column headings for each input data line. When VH and MG Lines are used, a separate insert will be printed directly beneath the MG Line showing any default values supplied by the computer.

**Part 2 - Controlling Wave Heights, Spectral Peak Wave Period, and Wave Crest Elevations**

This is a list of the calculated controlling wave heights, spectral wave peak periods, and wave crest elevations at the end point of each fetch and obstruction of the input, and at calculation points generated between the input stations.

**Part 3 - Location of Areas Above 1-Percent-Annual-Chance Surge**

This is a list of the locations of areas where the ground elevation is greater than the 1-percent-annual-chance stillwater (surge) elevation. Only areas identified by AS lines are listed.

**Part 4 - Location of Surge Elevations**

This is a list of the 10- and 1-percent-annual-chance stillwater (surge) elevations and the stationing of the points where each set of SWELs first becomes fully effective.

**Part 5 - Location of V Zones**

This is a list of the locations of the V/A Zone boundary and locations of the V Zone areas relative to these boundaries. The stationing is given for each V/A Zone boundary. The locations of the V Zone areas in relation to these boundaries are given as windward or leeward of the boundary.

**Part 6 - Numbered A Zones and V Zones**

This is a list of the zone data needed to delineate the flood hazard boundaries on the FIRM. The location of a flood zone boundary and the wave crest elevation at that boundary are given on the left. Between the boundary listings are the zone designations and FHFs. Under FEMA's Map Initiatives Procedure guidelines, all numbered V and A Zones should be changed to VE and AE Zones, respectively (elevations will not change), and the FHFs can be ignored (FEMA, 1991). When the same zone and elevation are repeated in the list, they should be treated as a single zone.

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## D.2.7 Mapping of Flood Elevations and Zones

Requirements for reviewing the initial model results and identifying flood insurance risk zones, guidance and examples for determining transects, and guidance for depicting the analysis on the FIRM are presented in this subsection.

[February 2002]

### D.2.7.1 Review and Evaluation of Basic Results

Prior to mapping the flood elevations and zones, the Mapping Partner shall review results from the models and assessments from a common-sense viewpoint and compare them to available historical data. When using these models, there is the potential to forget that the transects represent real shorelines of sandy beaches, rocky or cohesive bluffs, wetlands being subjected to extremely high water, waves, and winds. Familiarity and experience with the coastal area being modeled or similar areas should provide an idea of what is a "reasonable" result.

Use of the historical data is also very important in evaluating whether the results are reasonable. It would be very convenient if data from a storm closely approximating the 1-percent-annual-chance event were available, but this is seldom the case. Although most historical flood data are

for storms less intense than a 1-percent-annual-chance event, these data will still indicate, at a minimum, what areas should be in flood zones. For instance, if a storm that produced an extreme flood below the 1-percent-annual-chance SWEL generally caused structural damage to houses 100 feet from the shoreline, a "reasonable" Zone VE width must be at least 100 feet. Similarly, houses that collected flood insurance claims for the same storm should be at least in a Zone AE, AH, or AO. If the analyses of the 1-percent-annual-chance flood produce flood zones and elevations indicating lesser hazards than those recorded for a more common storm, the analyses should be reevaluated. One possible explanation can be that a new coastal structure acts to reduce flood hazards locally.

If there are indications that a reevaluation is needed, the Mapping Partner shall determine whether the results of the erosion assessment are appropriate. The Mapping Partner shall attempt to compare the eroded profile to past effects, whether in the form of profiles, photographs, or simply descriptions. A general idea of what happened previously can be sufficient. The Mapping Partner shall use judgment and experience to project previous storm effects to the 1-percent-annual-chance conditions and to ensure that the eroded profile is consistent with previous events.

The Mapping Partner shall examine other data input to the assessments of wave effects. This includes checking that the SWELs, wave heights, wave periods, and fetch lengths were used correctly and are consistent with the historical data. Further consideration might be given to examining if the buildings or structures modeled would be destroyed by the storm or if the buildings are on pilings above the flooding.

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The main point to be emphasized here is that the results should not be blindly accepted. There are many uncertainties and variables in coastal processes during an extreme flood and many possible adjustments to methodologies for treating such an event. The validity of any model is demonstrated by its success in reproducing recorded events. Therefore, the model results must be in basic agreement with past flooding patterns, and historical data must be used to evaluate these results.

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### D.2.7.2 Identification of Flood Insurance Risk Zones

The Mapping Partner shall identify the flood insurance zones and BFEs including wave heights be identified on each transect plot before delineating the flood insurance zones on the work maps, because of additional wave effects along with the 1988 redefinition of Coastal High Hazard Area to include the primary frontal dune. The existing topography, eroded transect, combination of shore effects in the wave envelope, and other results from wave overtopping assessment are all important to the proper identification of flood insurance risk zones.

Specifically, as discussed in Subsection D.2.1.2, the existing ground profile defines an appropriate extent of the primary frontal dune, as a ridge of sand bounded by relatively steep slopes. As discussed in Subsection D.2.4.5, the eroded transect for cases of duneface retreat may imply that flood hazards due to wave overtopping extend into an area landward of the WHAFIS results. In addition, as discussed in Subsection D.2.5.7, wave overtopping of stable shore barriers can result in flooding to areas above the mean elevation of wave runup. However, the

main consideration for integrated treatment of wave-controlled flood elevations is to define the wave envelope joining height and runup effects.

This wave envelope is a combination of representative wave runup elevation with the controlling wave crest profile determined by WHAFIS. The wave crest profile is plotted on the transect from the data in Part 2 of the WHAFIS output. A horizontal line is extended seaward from the wave runup elevation to its intersection with the wave crest profile to obtain the wave envelope, as shown in Figure D-25. If the runup elevation is greater than the maximum wave crest elevation, the wave envelope will be a horizontal line at the runup elevation. Conversely, if the wave runup is negligible or was not modeled, the wave crest profile becomes the wave envelope.

Flood insurance risk zones are defined basically by the wave envelope along with the general zone descriptions in Table D-13. Those results are supplemented by runup and overtopping considerations, as introduced previously. The following material outlines the process of flood insurance risk zone identification, with specific examples presented in the next section to illustrate some usual results.

**Table D-13. Descriptions of Coastal Flood Insurance Risk Zones**

| | |
|---|---|
| Zone VE | Coastal High Hazard Areas where wave action and/or high-velocity water can cause structural damage in the 1-percent-annual-chance flood. These areas are primarily identified by: (1) the area where 3-foot or greater wave height could occur (this is the area where the WHAFIS wave crest profile is 2.1 feet or more above the SWEL), (2) the area where the eroded ground profile is 3 feet or more below the representative runup elevation, and (3) the entire primary frontal dune, by definition. Subdivided into elevation zones with BFEs assigned. |
| Zone AE | Areas of inundation by the 1-percent-annual-chance flood, including wave heights less than 3 feet and runup elevations less than 3 feet above the ground. These areas are also subdivided into elevation zones with BFEs assigned. |
| Zone AH | Areas of shallow flooding or ponding, with water depths of 1 to 3 feet. These areas are usually not subdivided, and a BFE is assigned. |
| Zone AO | Areas of sheet-flow shallow flooding where overtopping water flows into another flooding source. These areas are designated with 1-, 2-, or 3-foot depths of flooding. |
| Zone X | Areas above 1-percent-annual-chance flood inundation. On the FIRM, shaded Zone X is inundated by the 0.2-percent annual chance flood, unshaded Zone X is above the 0.2-percent annual chance flood. |

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For a complete listing of flood insurance risk zones, refer to Section 1.4.2.7.1 of Volume 1 of these Guidelines.

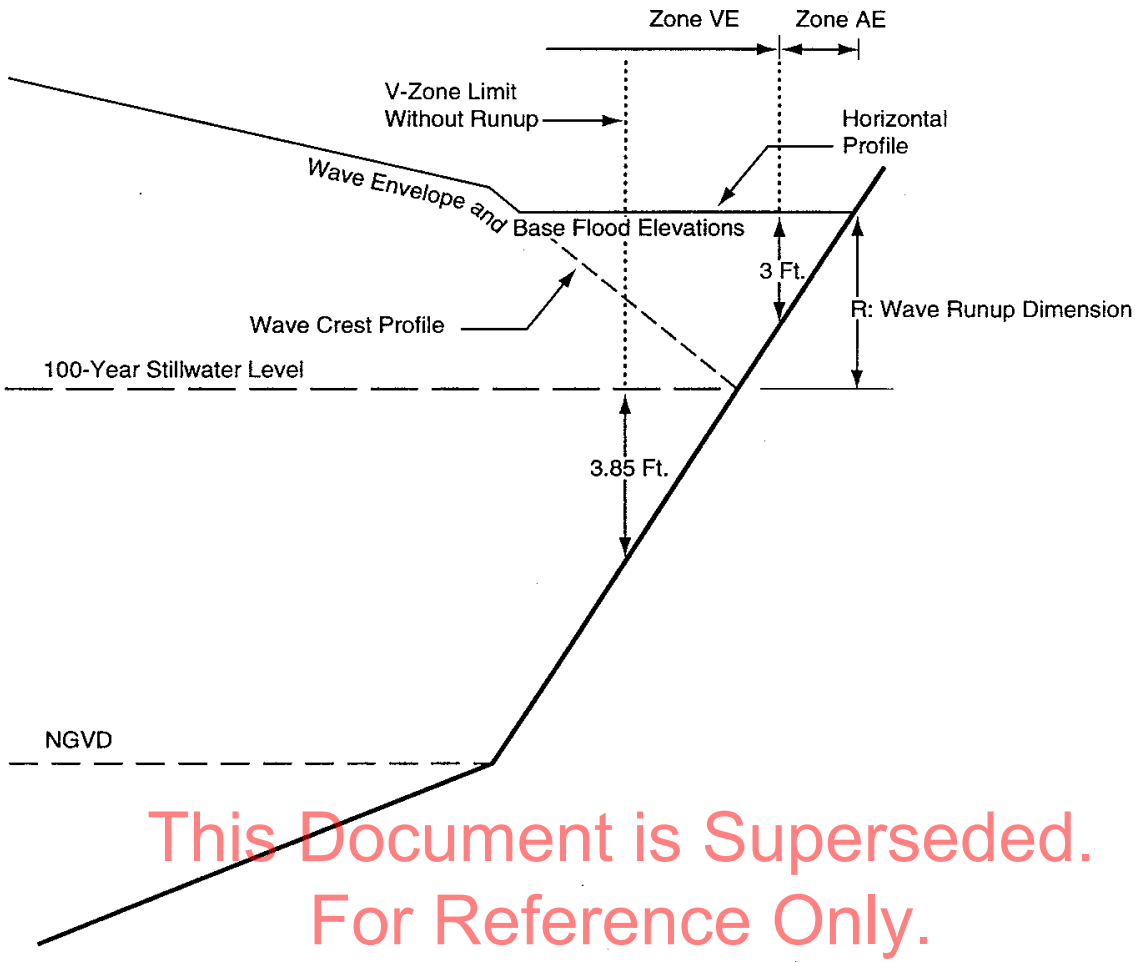


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**Figure D-25. Wave Envelope Resulting from Combination of Nearshore Crest Elevations and Shore Runup Elevation**

The first step in identifying the flood insurance risk zones on the transect is locating the inland extent of the VE Zone, also known as the VE/AE boundary. The VE-Zone limit for each of the three criteria is identified, and the VE/AE boundary placed at the one furthest landward, as shown in Figure D-26. The Mapping Partner may need to move that boundary further inland in the vicinity of a wave barrier where severe overtopping is indicated for the 1-percent-annual-chance flood, so high-velocity impacts occur over a limited landward area.

The Mapping Partner shall extend the Zone AE from the VE/AE boundary to the inland limit of 1-percent-annual-chance inundation, which is a ground elevation equal to the representative runup elevation, or the 1-percent-annual-chance SWEL if runup is negligible. The Mapping Partner may designate additional areas of shallow flooding or ponding for the 1-percent-annual-chance event as Zone AH or Zone AO. In cases of severe wave overtopping effects, a VE Zone may abut areas designated as Zone AH or Zone AO. The Mapping Partner shall label all areas above the 1-percent-annual-chance inundation as Zone X.

The Mapping Partner shall then subdivide the Zone AE and VE areas into elevation zones with whole-foot BFEs assigned according to the wave envelope. Ideally, the Mapping Partner would establish an elevation zone for every BFE in the wave envelope; but because these zones are mapped on the FIRM so that buildings or property can be located in a flood insurance risk zone, the Mapping Partner shall use a minimum width for the mapped zone to provide a usable FIRM. For coastal areas, the minimum zone width is 0.2 inch on the FIRM. For identifying elevation zones on the transect, the minimum width is 0.2 times the final FIRM scale; for example, a width of 80 feet for a FIRM at a scale of 1 inch equals 400 feet, or a width of 100 feet for a FIRM at a scale of 1 inch equals 500 feet.

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The Mapping Partner shall not subdivide the horizontal runup portion of the wave envelope, if any; the runup elevation, rounded to the nearest whole foot, is the BFE. The Mapping Partner shall subdivide the WHAFIS wave crest profile. Generally, the VE Zone is subdivided first. Initially, the Mapping Partner shall mark the location of all elevation zone boundaries on the transect. Because whole-foot BFEs are being used, these should always be at the location of the half-foot elevation on the wave envelope.

The Mapping Partner shall combine elevation zones that do not meet the minimum width with an adjacent zone or zones to yield an elevation zone wider than the minimum. The BFE for this combined zone is a weighted average of the combined zones. Often, in subdividing VE Zones, the maximum BFE is located just inside the mapped shoreline, and the remainder of the VE Zone is then subdivided into elevation zones of the minimum width.

The Zone AE, if wide enough, shall be subdivided in the same manner. If the total AE Zone is less than the minimum width, the lowest elevation VE Zone is usually assigned to that area. This situation typically occurs for steep or rapidly rising ground profiles, and it is not unreasonable to designate the entire inundated area as a VE Zone. In some cases, however, it may be appropriate for the Mapping Partner to extend the AE Zone slightly into the next zone seaward in order to satisfy the minimum width requirement.

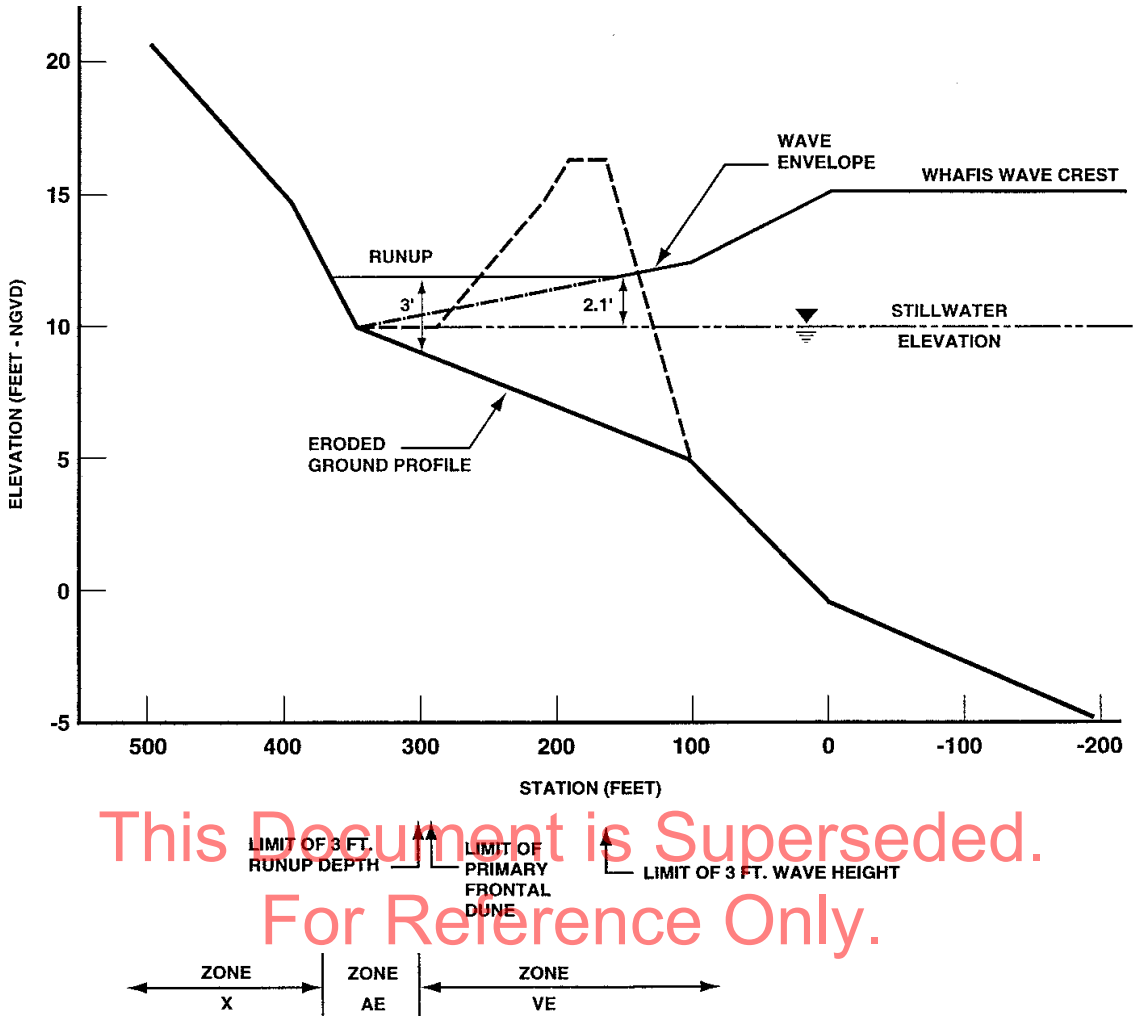


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**Figure D-26. Possible V-Zone Limits at Eroded Dune**

Relatively low areas inland of zones with assigned wave elevations may be subject to shallow flooding or ponding of flood water; the Mapping Partner shall designate these areas as Zone AH or Zone AO. Such designations can be relatively common landward of coastal structures and dunes, where wave overtopping occurs. Identifying appropriate zones and elevations may require particular care for dunes, given that the entire primary frontal dune is defined as Coastal High Hazard Area. Although the analyses may have determined a dune will not completely erode and wave action should stop at the retreated duneface with only overtopping possibly propagating inland, the Mapping Partner shall designate the entire dune as Zone VE. The Mapping Partner shall assign the BFE at the duneface for the remainder of the dune.

It may seem unusual to use a BFE that is lower than the ground elevation, although this is actually fairly common. Most of the BFEs for areas where the dune was assumed to be eroded are also below existing ground elevations. In these cases, it is the VE Zone designation that is most important to the NFIP, under current regulations, structures in VE Zones must be built on pilings and prohibits alterations to the dune.

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### D.2.7.3 Transect Examples

Figure D-26 provides a schematic summary for the three criteria potentially defining the landward limit to the Coastal High Hazard Area. The examples discussed below depict idealized transects of typical types to illustrate common flood hazard zonations in a quantitative way. Coastal erosion is a dominant consideration for the first set of examples. The second set of examples addresses some usual effects at stable shore barriers exposed to extreme wave action.

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Figure D-27 presents an example of dune removal with appreciable runup occurring on the eroded profile. For this transect, the VE Zones with BFEs of 13, 14, and 15 feet are too narrow to be mapped, so they are averaged to a BFE of 14 feet. The Zone VE, elevation 12 feet, is enlarged slightly to include some of the elevation 13-foot area so that the boundary would be located at the dune toe or 5-foot contour line, a feature easily identified on the work map. The boundary between the Zone VE, elevation 14 feet and the Zone VE, elevation 16 feet is located just landward of the shoreline. The Zone AE, elevation 12 feet, in Figure D-27 is only 70 feet wide, slightly less than the minimum mapping width. In this example, the Mapping Partner would have to examine the work map to determine if this zone might be wider or narrower in the contiguous area. If wider, the Zone AE should be used; if narrower, the designation extended through this area should be Zone VE, elevation 12 feet.

Figure D-28 illustrates an example of a relatively high retreated duneface. A mean runup elevation of 13 feet is calculated for the eroded duneface. This elevation is assigned through the dune, all of which is designated as Zone VE. Because the dune remnant extends more than 7 feet above the SWEL, no flooding landward of the dune is indicated by designating the area as Zone X. Note that the retreated dune profile shifts the 0.0 foot elevation shoreline 65 feet seaward. Because the existing 0.0 foot elevation shoreline is used on the work map, the Zone VE, elevation 16 feet, is located just landward of the existing shoreline.

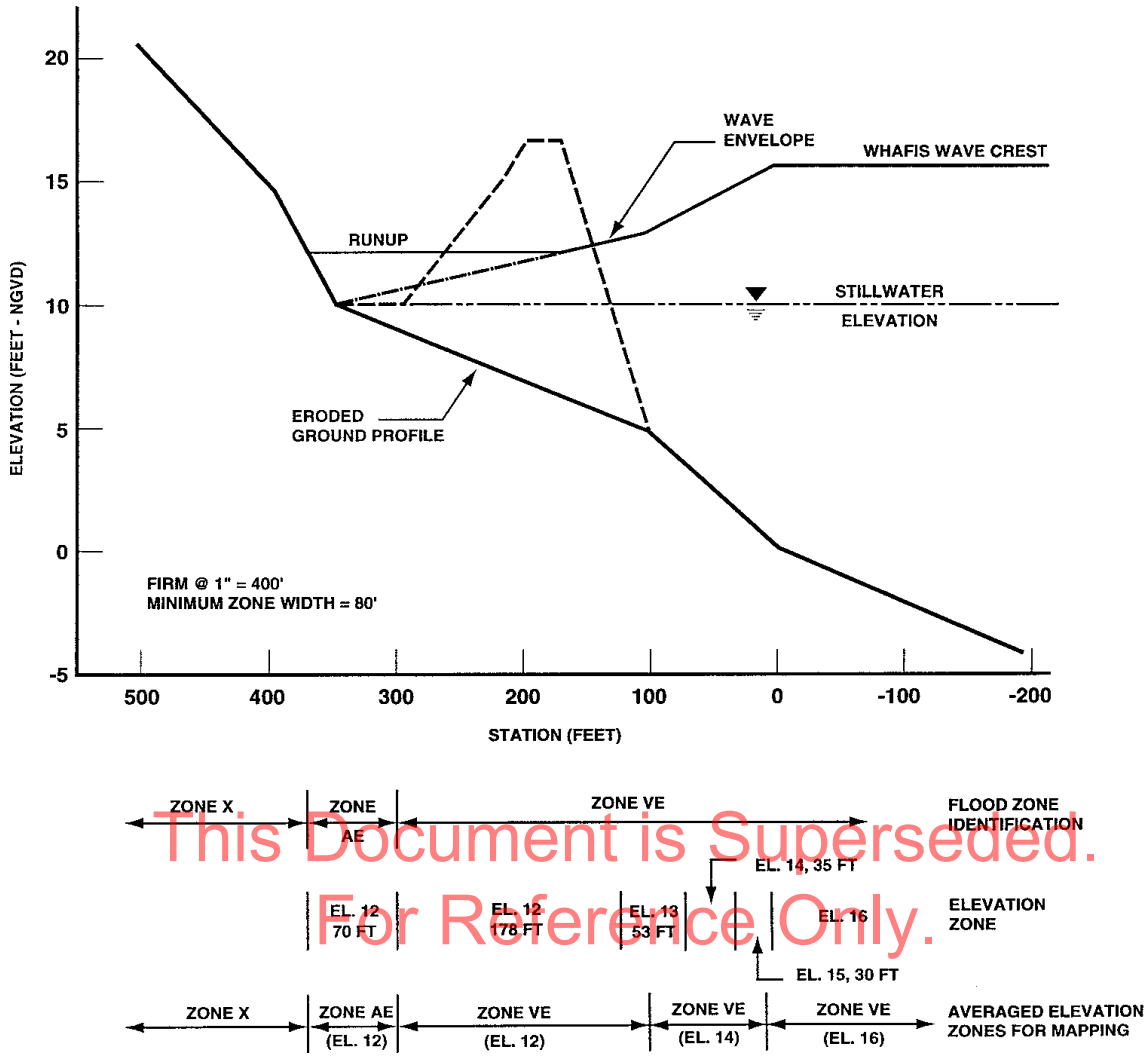


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**Figure D-27. Identification of Elevation Zones, Example 1: Dune Removal with Wave Runup Landward**

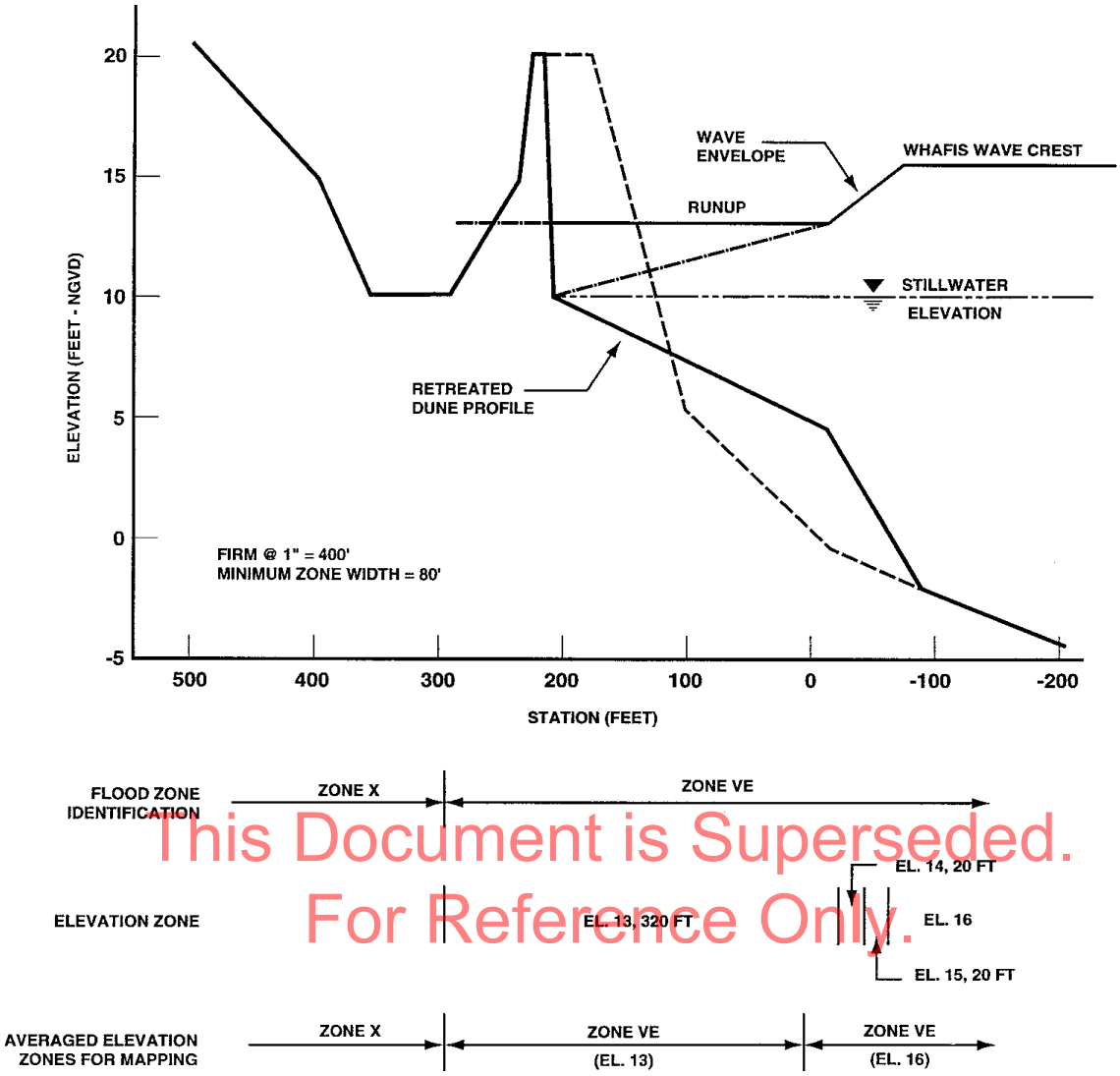


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**Figure D-28. Identification of Elevation Zones, Example 2: Duneface Retreat with Relatively High Remnant.**

Figure D-29 illustrates an example of a retreated duneface with a relatively small remnant having low relief. A mean runup elevation of 12 feet is calculated for the eroded profile, and this flood elevation is assigned through the dune, all of which is designated as Zone VE . The division into separate map zones is similar to the division in Figure D-28. Because the dune remnant extends less than 7 feet above the SWEL, appreciable wave overtopping is expected during the 1-percent-annual-chance flood. An area landward of the dune of about the minimum mapping width is designated as a Zone AO, depth 1 foot.

Figure D-30 illustrates an example of dune removal where there is some runup and overtopping of the remaining stub. As in Figure D-27, the VE Zone with a runup elevation of 11 feet is extended to the dune toe and the Zone VE, elevation 16 feet, is located just landward of the shoreline. Although elevation 14 feet is shown on Figure D-30 for the intermediate VE Zone, elevation 13 feet could also be used; adjacent transects should be examined and a compatible BFE should be selected. Also note that the boundary between the Zone AO, depth 1 foot, and the Zone AE, elevation 7 feet, is at the intersection of the SWEL and ground profile.

An eroded bluff is shown in Figure D-31. The angle of the bluff face remains the same while the seaward extension from the toe is a 1:40 slope. The computed runup elevation slightly exceeds the bluff crest and is higher than the maximum wave crest elevation. The area is designated Zone VE, elevation 18 feet, until the difference between the runup elevation and the ground is less than 3 feet. In this figure, the Zone AE, elevation 18 feet, is slightly narrower than the minimum mapping width. As was recommended for the example in Figure D-27, the neighboring area on the work map should be examined to determine if this zone should be mapped. AE Zones are usually not mapped for bluffs unless computed runup exceeds the bluff crest, as shown in Figure D-31. (Note: Figures D-16 and D-17 outline another flooding treatment of bluffs where computed runup is well above the crest.)

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On sandy shores, transects usually are extended across barrier islands, marshes, inland water bodies, etc., such that at least two VE Zones can be identified. Procedures in these cases are the same, with elevation averaging also very common. With a little practice, identification of the flood zones and elevations becomes fairly routine using the wave envelope and transect profile.

With shore structures having steep slopes, runup elevations are relatively high and a wide range of wave hazards can occur, including erosion or scour near the structure. These circumstances may result in a variety of distinct and compact situations, where appreciable engineering judgment can be required for appropriate assessment of flood hazards.

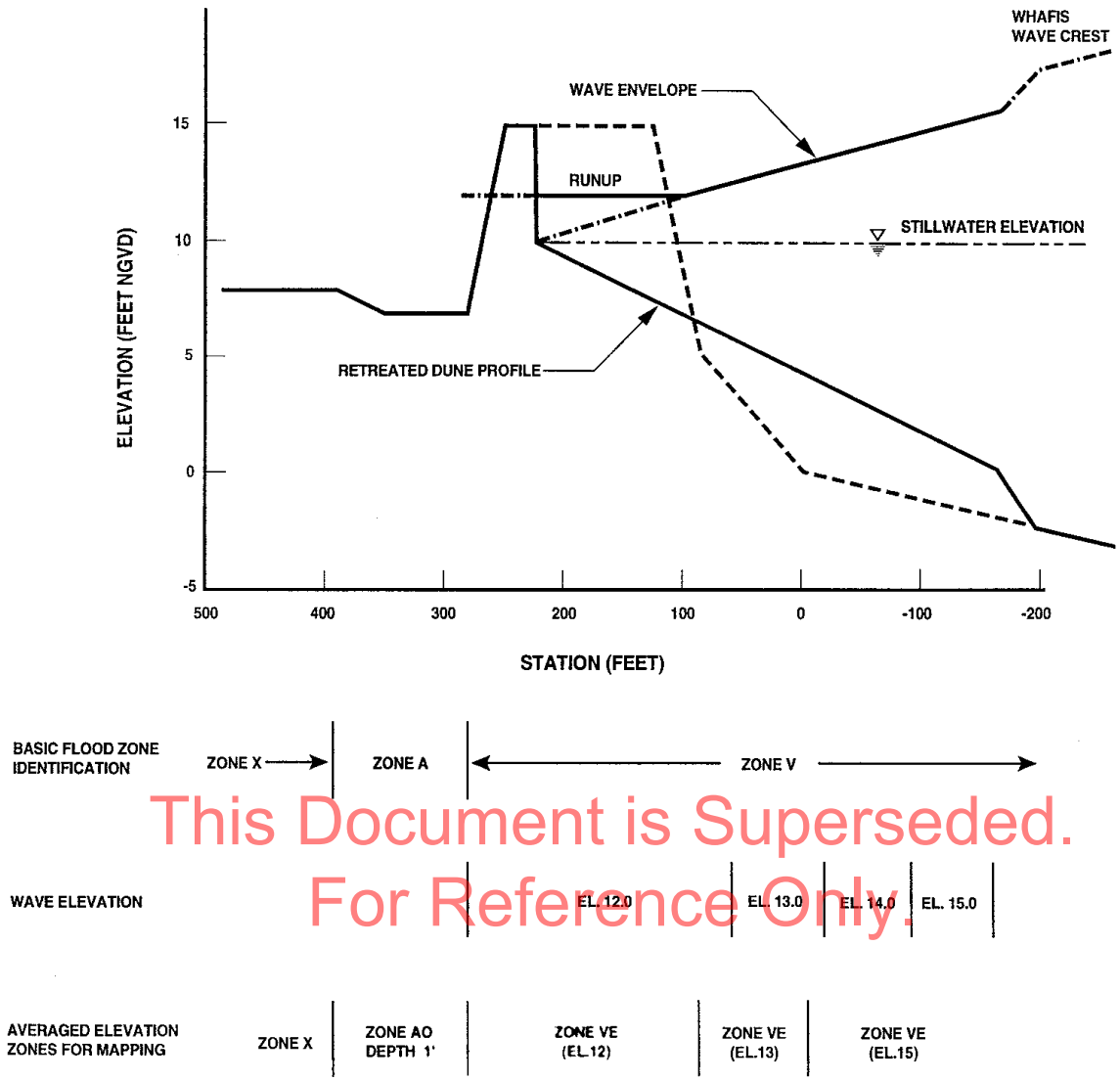


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**Figure D-29. Identification of Elevation Zones, Example 3: Low Retreated Dune with Wave Overtopping.**

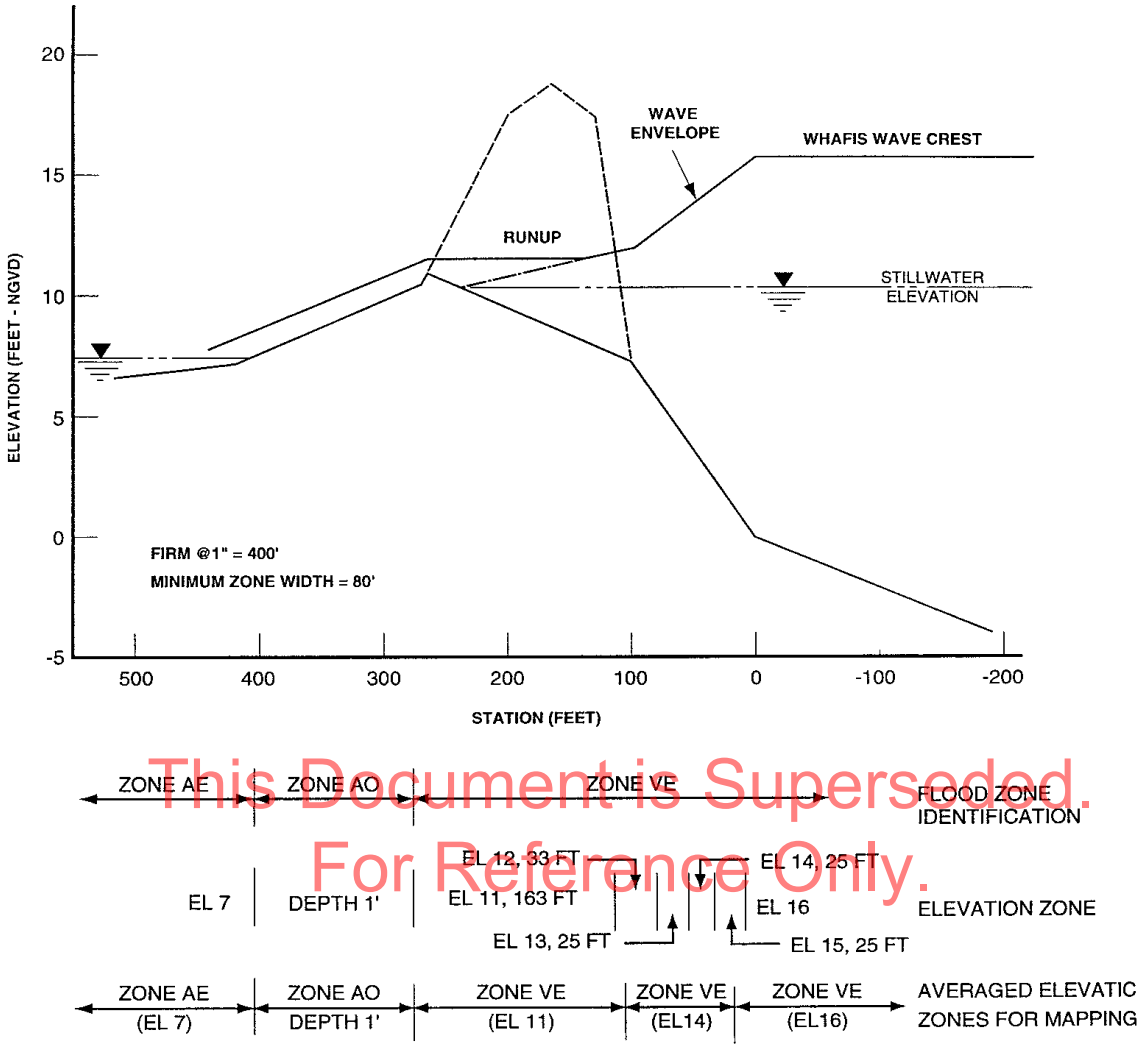


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**Figure D-30. Identification of Elevation Zones, Example 4: Dune Removal with Wave Runup and Runoff**

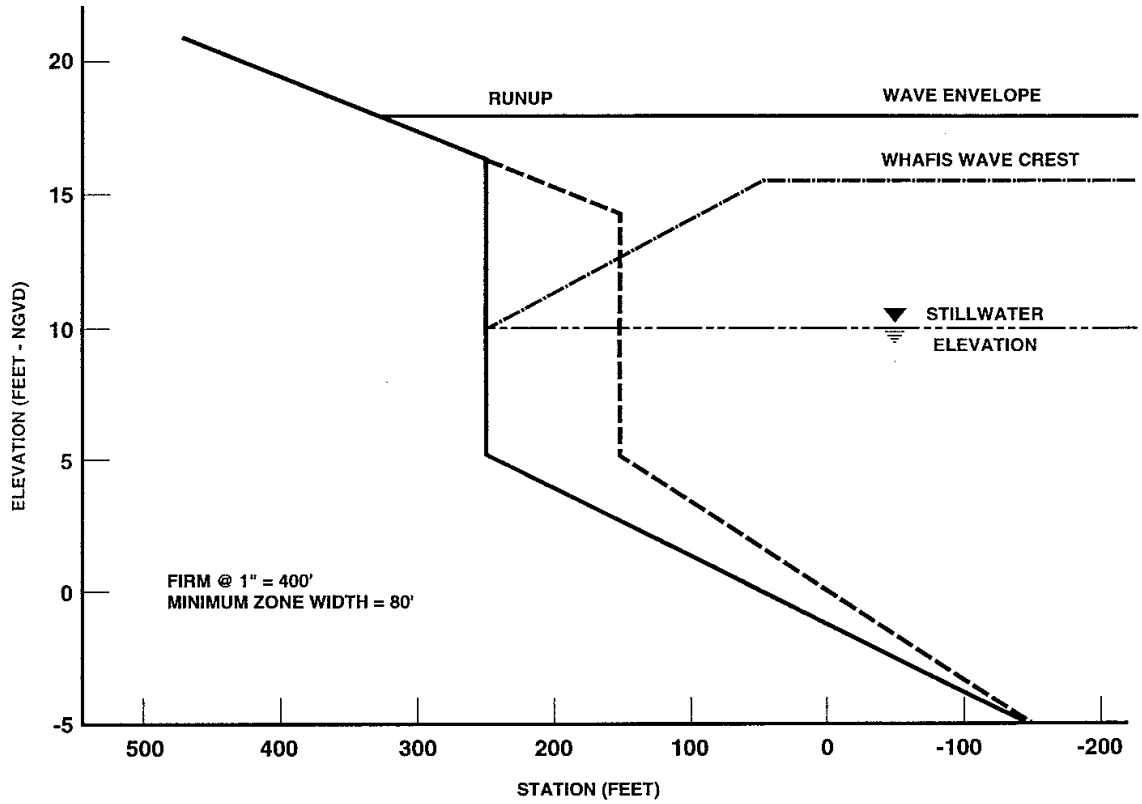


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**Figure D-31. Identification of Elevation Zones, Example 5: Eroded Bluff with Wave Runup**

Figures D-32, D-33, and D-34. illustrate schematic effects for a few basic configurations, presuming the structures remain intact through the 1-percent-annual-chance flood and no appreciable shore erosion occurs

Figure D-32 illustrates an example of moderate structure overtopping expected for waves accompanying the 1-percent-annual-chance flood. The structure crest has sufficient freeboard above the 1-percent-annual-chance SWEL to contain a calculated mean runup of 6 feet, but extreme wave runups are likely to overtop the structure intermittently. The entire extent of shore structure is treated as a unit and designated as a VE Zone, and is assigned the mean runup elevation of 16 feet. Landward of the structure, an area with at least the minimum mapping width is appropriate for designation as Zone AO, depth 1 foot, with the extent of the zone depending on ground profile.

Figure D-33 illustrates an example of a structure extending above the 1-percent-annual-chance SWEL but heavily overtopped by wave action. The calculated mean runup elevation is 5 feet above the seaward face, but that is reduced to the maximum excess runup of 3 feet in assigning a flood elevation of 16 feet for the shorefront VE Zone. That zone extends through the entire structure and over an additional 30 feet landward, because likely wave impact area reaches beyond the structure during the 1-percent-annual-chance flood. Cumulative wave overtopping yields ponding within an additional landward area that is 100 feet wide, which is designated as Zone AO, depth 2 feet.

Figure D-34 illustrates an example of a structure covered by 3 feet of water during the 1-percent-annual-chance flood. Flood depth is not sufficient for waves 3 feet in height to propagate inland of the structure, but the V Zone must extend to 30 feet landward of the structure, in view of likely wave effects through the flood's course. The shore structure is too narrow for multiple V Zones to be delineated, so there is one designation of Zone VE, elevation 13 feet. Landward of that zone, further wave hazards occur in the Zone AE, elevation 11 feet.

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In examining Figures D-32, D-33, and D-34, it may seem surprising that relatively high structures can result in higher flood elevations, compared to an inundated structure. However, a structure with more freeboard can deflect incident wave action to greater elevations during the 1-percent-annual-chance flood, so the present zonations are physically appropriate. The hazard zonations landward of coastal structures generally have more importance, and they reflect the greater protection provided by higher but durable structures.

[February 2002]

### D.2.7.4 Mapping Procedures

Properly integrated delineation of the results of flooding analyses involves judgment and skill in reading topographic and land cover maps. The time and effort put forth to determine the flood elevations and extents will be negated if the results of these analyses are not properly delineated on the FIRM. The FIRM is usually produced from the work maps described in Subsection D.2.2. Therefore, the Mapping Partner shall transfer the flood zones and elevations identified on the transects to the work maps and interpolate boundaries between transects. The Mapping Partner shall set up the work maps with contour lines, buildings, structures, vegetation, and

transect lines clearly located. Because roads are often the only fixed physical features shown on the FIRM, the

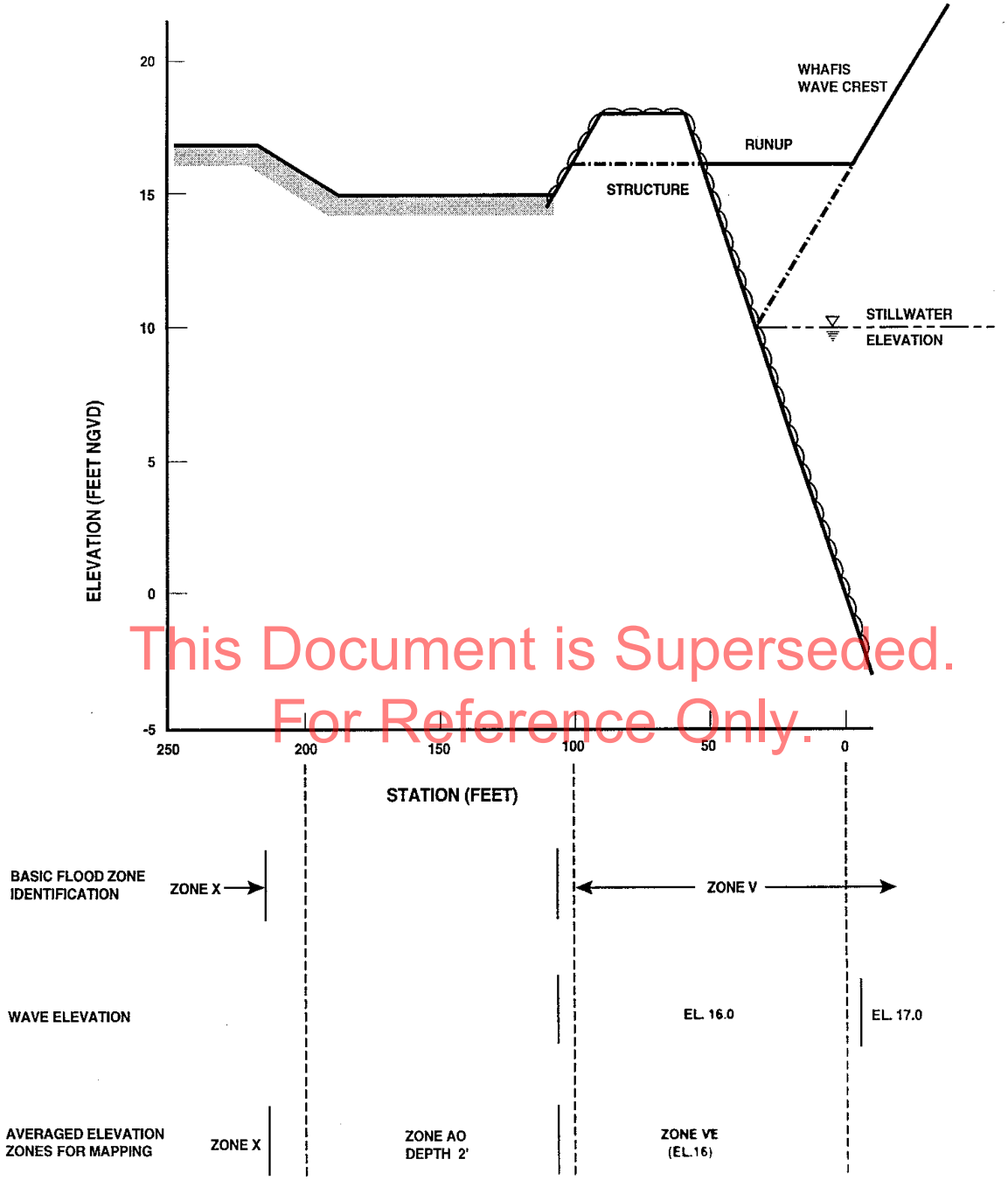


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**Figure D-32. Identification of Elevation Zones, Example 6: Coastal Structure with Moderate Wave Overtopping**

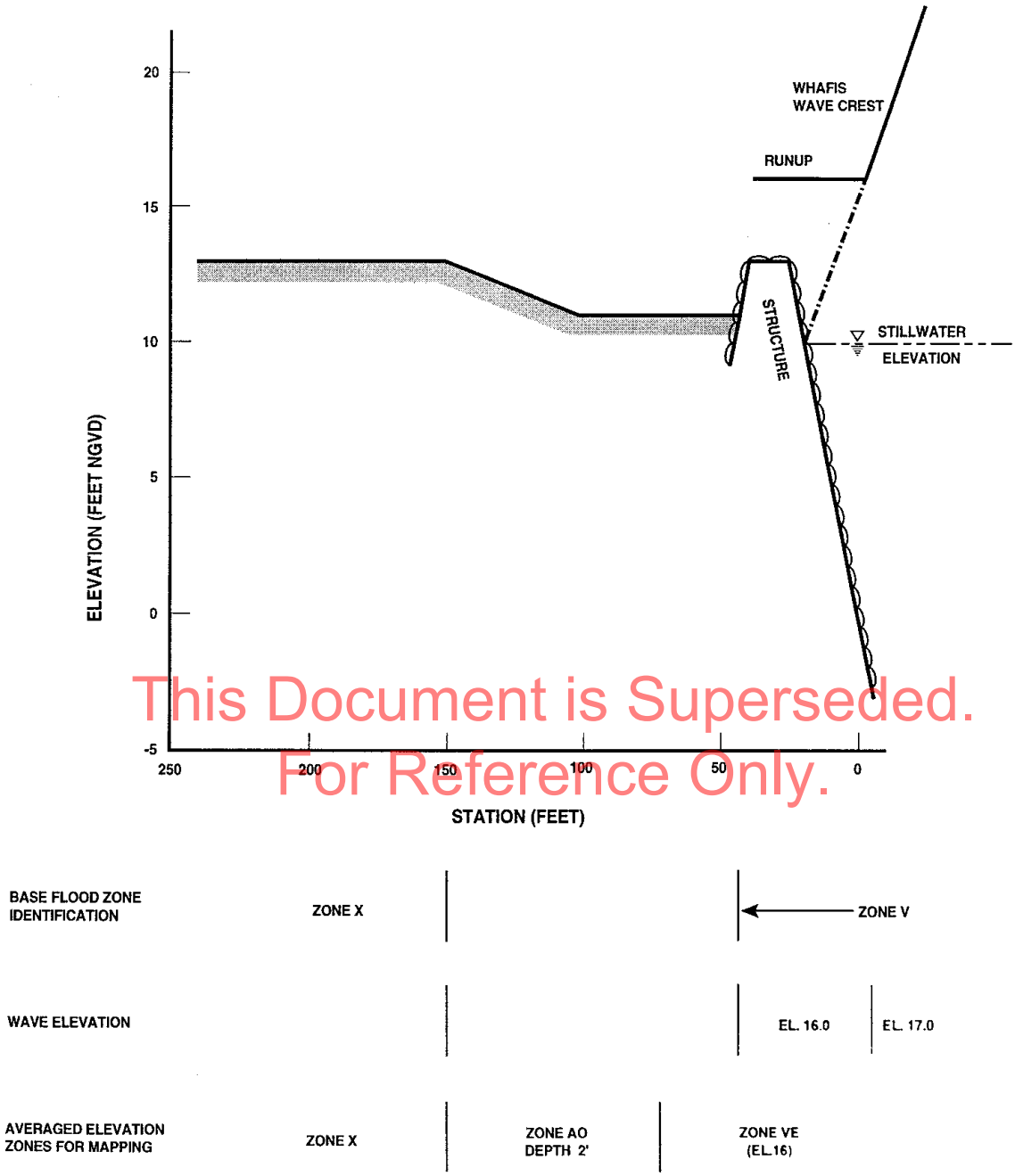


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**Figure D-33. Identification of Elevation Zones, Example 7: Coastal Structure with Severe Wave Overtopping**

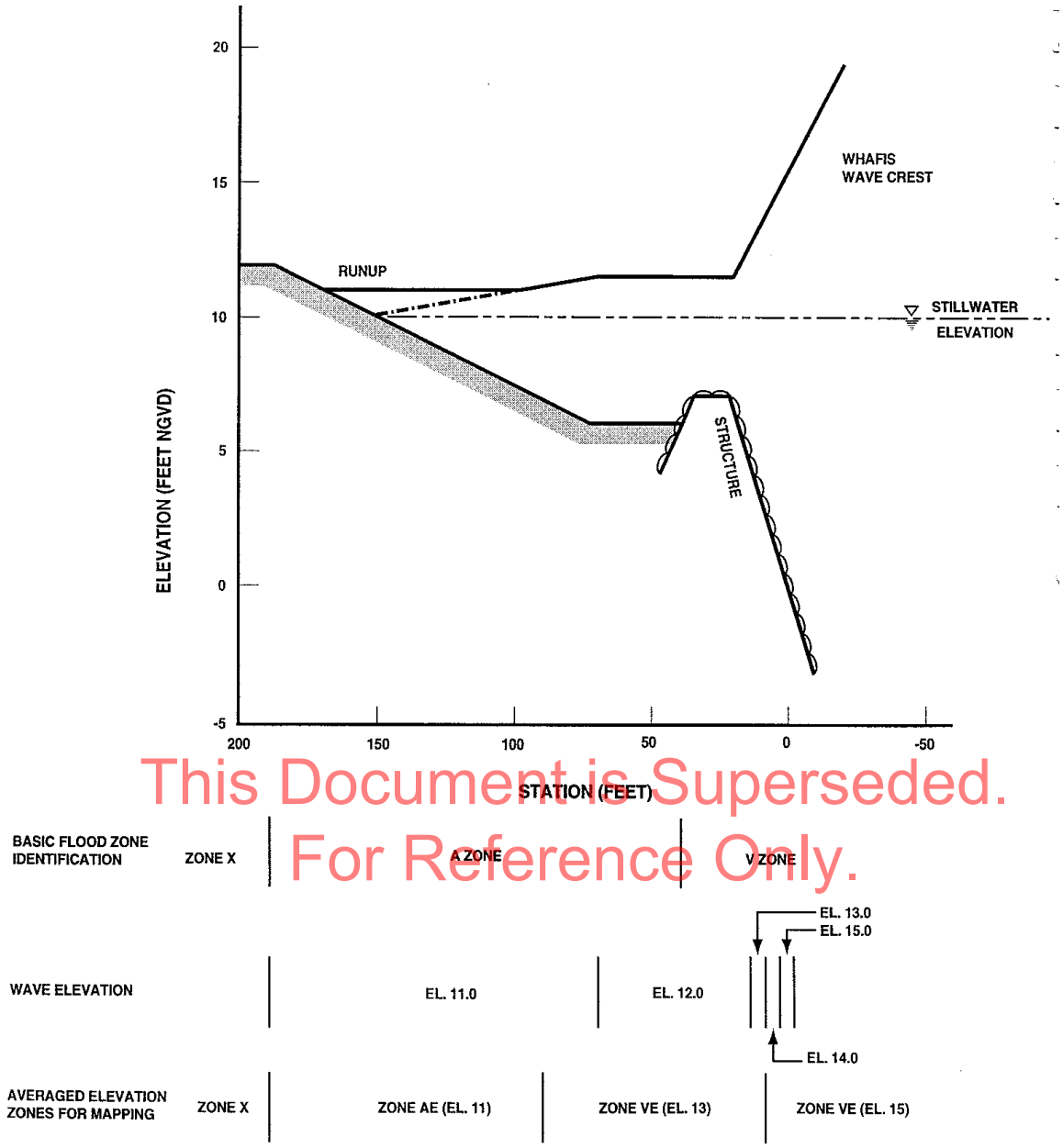


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**Figure D-34. Identification of Elevation Zones, Example 8: Coastal Structure with Inundation**

Mapping Partner shall ensure that other features and the flood zone boundaries are properly located on the work maps in relation to the centerline of the roads as they will appear on the FIRM.

For each transect, the Mapping Partner shall transfer the identified elevation zones from the transect to the work maps, marking the location of the boundaries along the transect line so that boundary lines can be interpolated between transects. The Mapping Partner shall ensure that boundaries are marked at the correct location. Because of erosion assumptions, the location of the elevation 0.0 shoreline changes on the transect but not the work maps.

Using the transect profile, the Mapping Partner shall determine the location of the zone change in relation to a physical feature (e.g., ground contour, back side of a row of houses, 50 feet into a vegetated area) and delineate the boundary line for the area represented by that transect along this feature. The Mapping Partner shall measure the widths of the zones carefully; zones that narrow to less than 0.2 inch must be tapered to an end. Likewise, if the zone becomes much wider, it may be possible to break an averaged elevation zone into two mapped elevation zones.

One of the more difficult steps in delineating coastal flood zones and elevations is the transition between transect areas. Good judgment and an understanding of typical flooding patterns are the best tools for this job. Initially, the Mapping Partner shall locate the area of transition (an area not exactly represented by either transect) on the work maps. The Mapping Partner shall then delineate the floodplain boundaries for each transect up to this area. The Mapping Partner shall examine how a transition can be made across this area to connect matching zones and still have the boundaries follow logical physical features. Other transects similar to this area could give an indication of flooding. Sometimes the elevation zones for the two contiguous transects are not the same; in such cases, the Mapping Partner may have to taper the zones to an end or enlarge the zones and subdivide them in the transition area.

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Communities with significant flooding hazards from wave runup may have one transect representing more than one area because the areas have similar shore slopes. In this case, the Mapping Partner shall identify the different areas and delineate the results of the typical transect in each area. Transition zones may be necessary between areas with high runup elevations to avoid large differences in BFEs and to smooth the change in flood boundaries. These zones are to be fairly short and cover the shore segment with a slope not exactly typical of either area. The Mapping Partner shall determine the transition elevation using judgment in examining runup transects with similar slopes. The Mapping Partner shall not use transition zones if there is a very abrupt change in topography, such as the end of a structure.

Lastly, Mapping Partner shall map the Zone X areas. The Mapping Partner shall show areas below the 0.2-percent annual chance SWEL that are not covered by any other flood zone as Zone X (shaded) on the FIRM. Often the maximum runup elevation is higher than the 0.2-percent-annual-chance SWEL; in such cases, the Zone X (shaded) designation will be used in that area. All other areas are designated Zone X without shading.

Because flood elevations are rounded to the nearest whole foot, the Mapping Partner does not need to spend hours resolving a minor elevation difference. Also, because structures or proposed structures must be located on the FIRM, the Mapping Partner shall attempt whenever possible to smooth the boundary lines and to follow a fixed feature such as a road. In preparing the FIRM,

the Mapping Partner shall ensure that the mapped results are technically correct and but the FIRM is easy for the local insurance agent, building inspector, or permit officer to use.

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## D.2.8 Required Documentation

The Mapping Partner shall fully document the coastal flood hazard determination for each affected community. Because FIS Reports and FIRMs form the basis of Federal, State, and local regulatory and statutory enforcement mechanisms and are subject to administrative appeal and litigation, Mapping Partners shall ensure that all technical processes and decisions are recorded and documented. The FIS Report may not contain all the documentation that would be needed for a response in the event that the study results are questioned. Therefore, the Mapping Partner shall prepare an engineering report for each study. This report will provide detailed data needed by FEMA or the community to reconstruct or defend the study results on technical grounds. The minimum information required for the engineering report is summarized below.

**Basic Data**.

In this section, the Mapping Partner shall include all contacts made to obtain data for the study. All basic data used must be fully referenced and, if possible, reproduced in the report. All historical flood information must be documented in this section, even if the Mapping Partner did not use the information in quantitative analyses.

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**Transects**

The Mapping Partner shall show all transects on a transect location map. Each transect must be plotted separately and show the erosion assessment, input data for wave models, wave envelope, and zone determination.

**Model Input and Output**

The Mapping Partner shall provide computer printout listings for input and output data for both the Wave Runup and Wave Height Models for all the transects. These listings must be keyed to the transect location map and transect plots.

**Study File**

During the course of the study, the Mapping Partner shall maintain a file containing records of all coordination, activities, and decisions. This is especially important where nonstandard approaches were used and engineering judgment played a significant role. The Mapping Partner shall ensure this file meets the requirements for a Technical Support Data Notebook as documented in Appendix M of these Guidelines.

[February 2002]

# D.3 Wave Elevation Determination and V Zone Mapping: Great Lakes

Methodologies for determining coastal flood elevations and flood insurance risk zones have been adopted and refined over a period of time, as recounted in Section D.2 and in FEMA's *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping* (1995). Standard treatments for U.S. seacoast sites address wave heights, wave crest elevations, wave runup, and coastal erosion accompanying the 1-percent-annual-chance flood (FEMA, 1995). The effects of such waves determine flood elevations and the extent of Coastal High Hazard Areas (V Zones).

Until recently, wave effects were not taken into account along Great Lakes shores, but storms during the high water levels from 1985 to 1987 prompted reconsideration of this omission. A USACE study in 1989 concluded that recent significant storm damage at New York, Michigan, and Illinois sites confirmed the importance of wave runup contributions to actual coastal flooding on the Great Lakes. That finding led to specific calculation procedures to determine runup elevations appropriate to Great Lakes coasts with barriers to wave propagation (FEMA, 1991). Later, the standard NFIP seacoast model for wave height analysis was modified to apply to the lower wind speeds typical of Great Lakes events, and a detailed review addressed wave conditions and coastal erosion processes and quantities accompanying extreme floods at various U.S. lake sites (Dewberry & Davis, 1995). All necessary guidance has now been developed for treating wave effects in communities located along the Great Lakes

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This subsection unifies the technical policies, procedures, and methodologies relevant to conducting a flood hazard study for a Great Lakes coastal community. In addressing coastal studies for specific geographical regions, these Guidelines and FEMA's *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping* (1995) serve as user guides. Appropriate application of this guidance, along with an understanding of coastal engineering principles, will assist Mapping Partners in determining coastal flooding elevations and hazards and presenting this information on the FIRM.

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## D.3.1 Appropriate Treatments

The methodologies that shall be used to treat all the wave hazards possibly associated with a 1-percent-annual-chance flood are summarized in Table D-14. However, Mapping Partners must recognize that not every wave effect that occurs on the Great Lakes must be addressed for every flood hazard study or for every lakeshore community. To minimize unnecessary effort, it is useful early in the study process to identify those wave effects that can contribute noticeably to the BFEs and thus should be analyzed. Whether or not a wave treatment is appropriate depends primarily on the basic type of coastal topography, as outlined in Table D-14.

**Table D-14. Important Wave Treatments for Typical Coastal Topographies**

| COASTAL TOPOGRAPHY | IMPORTANT WAVE TREATMENTS | | |
|---|---|---|---|
| | EROSION | RUNUP | WHAFIS |
| Rocky bluff | | x | x |
| Sediment bank or bluff | x | x | x |
| Sandy beach, small dunes | x | | x |
| Sandy beach, large dunes | x | x | x |
| Open wetlands | | | x |
| Shore protection structure | | x | x |

The objective of a coastal study is to provide legible and accurate flood hazard maps with appropriate BFEs including wave contributions. Although procedures to define V Zones are fully documented in these Guidelines, mapping V Zones may not be appropriate in some Great Lakes areas. Both engineering and practical judgment are required for a proper decision on this matter. The typical study finding is a narrow V Zone, making its usefulness uncertain on maps at usual scales. Also, relatively small numbers of existing coastal buildings are likely to be affected by possible V-Zone designations along some Great Lakes.

V Zones are to be mapped only when the Regional Project Officer (RPO) approves such action. Some common exceptions to required approval might include coastal areas lakeward of sizable bluffs or designated as primary frontal dunes, so that the V Zone can be clearly delineated.

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A flowchart with the basic study procedures for defining flood hazards in the Great Lakes region is presented in Figure D-35.

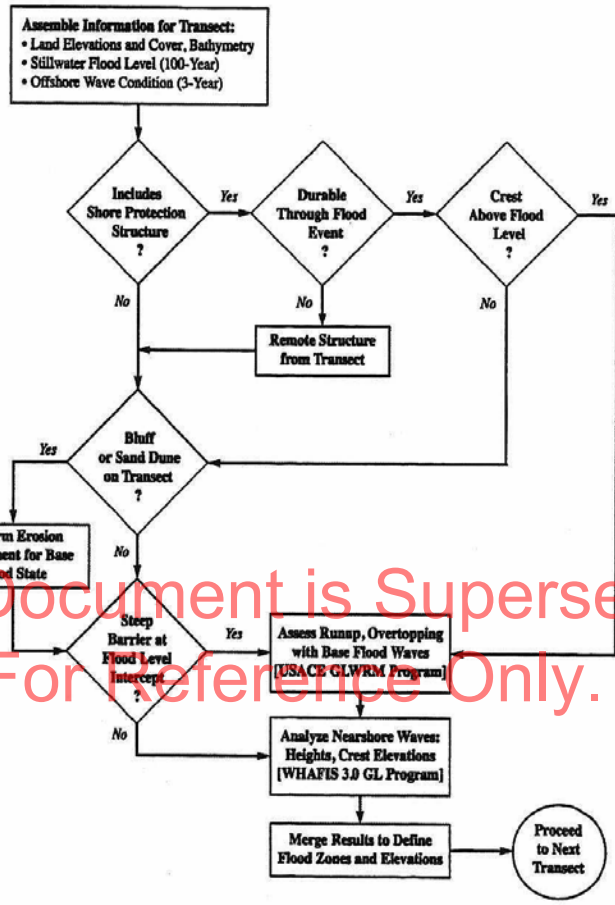


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**Figure D-35. Procedure for Defining Flood Hazards on Great Lakes Shores**

[February 2002]

## D.3.2 Data Requirements for Coastal Flood Hazard Analyses

A coastal flood hazard analysis begins with collecting the data and information required for the ensuing analyses, including the input needed for the computer models. The coastal models discussed here are executed along transects, which, as discussed earlier in this Appendix, are cross sections taken perpendicular to the mean shoreline to represent a segment of coast with similar characteristics. Thus, collected data are compiled primarily for use in developing transects and for locating and detailing the results on work maps. Work maps are to show the topography and land cover at a scale with sufficient detail to properly delineate the results of the analyses and interpolate between transects.

Data collection is to start at the community level and proceed with inquiries to appropriate county, State, and Federal agencies. To pursue any suggestions provided by government agencies, private firms specializing in topographic mapping or aerial photography may also be contacted.

This subsection describes the data requirements for coastal flood hazard analyses.

[February 2002]

### D.3.2.1 Stillwater Elevations

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The USACE's *Revised Report on Great Lakes Open-Coast Flood Levels* (1988) is FEMA's source for SWELs on the Great Lakes, at recurrence intervals of 10, 50, 100, and 500 years (reflecting 10-, 2-, 1-, and 0.2-percent-annual-chance flood elevations, respectively). Documented flood elevations pertain to specific U.S. reaches of open coast, defined as "lake shoreline which is unprotected by the presence of islands and which is uninterrupted by bays." These elevations are based on a standardized analysis of maximum annual water levels from long-term gage records (1900 to 1986) and are referenced to NGVD.

The USACE report on Great Lakes flood levels is divided into Phase I and Phase II reports. The Phase I report provides SWELs for most of the U.S. shoreline of Lake Superior (divided into five separate reaches), Lake Michigan (nine reaches), Lake Huron (eight reaches), Lake St. Clair (one reach), Lake Erie (24 reaches), and Lake Ontario (five reaches). In Subsection D.3.9, charts identifying separate reaches and the flood elevations on each lake are reproduced; except on Lake Erie, flood elevations usually remain constant over tens of miles along the shore. The Phase II report provides the flood levels for connecting channels and addresses general methods for developing flood levels in other areas, such as bays, inlets, and sheltered shorelines. For some of these areas, separate reports such as the "Saginaw Bay Flood Levels Report" for Lake Huron, have been prepared to document the SWELs (USACE, September 1989).

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### D.3.2.2 Transect Locations

Transects for coastal flood hazard analyses are to be located with careful consideration given to the physical and cultural characteristics of the land so that they will closely represent conditions in the vicinity of the transect. If they are carefully placed, excessive mapping interpolation of the BFEs between transects, as well as unnecessary study effort, can be avoided. The transects are to be placed more closely together in areas of complex topography, dense development, and unique flooding, and where computed wave heights and runup may be expected to vary significantly. Wider spacing may be appropriate in areas having more uniform characteristics. For example, a stretch of developed shoreline with various building densities, protective structures, and vegetation may require a transect every 1,000 feet or so, whereas a long stretch of undeveloped shoreline with a continuous dune or bluff of fairly constant height and shape, and similar landward features may require a transect only every 1 to 2 miles.

In areas where runup is significant, the location of transects is governed by variations in shore slope or steepness. In other areas where dissipation of wave heights is significant to the computation of flood hazards, transect location is based on variations in land cover, such as buildings and vegetation. Often, areas with similar characteristics may be scattered throughout a community, and the results from one transect are also representative of other locations and can be delineated accordingly.

The Mapping Partner performing the coastal flood hazard study shall locate transects on the work map to be submitted with the analysis, and shall compile the input data and displayed the data on individual profiles for each transect. The Mapping Partner shall take the data (e.g., topography, development, vegetation) not only at the transect site, but for the entire area or length of shoreline represented by the transect so that the input data depict average characteristics of the area. The Mapping Partner may divide the work map into transect areas to help in compiling the data.

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### D.3.2.3 Topographic Data

Topographic data must have a contour interval of equal or greater detail than that used for the effective FIS, and a minimum interval of 5 feet or 1.5 meters. While more detailed information, such as spot elevations or a smaller contour interval, can be useful in defining the dune or bluff profile and in delineating floodplain boundaries, it is required only when a map revision request with new coastal analyses is based on new detailed topographic data. As discussed in Volume 2, the data, usually in the form of maps, shall be certified and shall reflect current conditions in the area of the analysis or, at a minimum, conditions at a time more recent than the topographic data used in the effective FIS.

Topography must extend lakeward at least to the Low Water Datum defined for each Great Lake, as listed in Table D-14. The Low Water Datum corresponds to extremely low annual means of lake level during the 1900s and is described in terms of the International Great Lakes Datum of

1985 (IGLD85). The relation of NGVD29 to IGLD85 needs to be defined for each coastal flood hazard analysis site. NGVD29 is required as the datum for the topographic map.

If possible, the Mapping Partner shall check the shore topography to note any changes caused by construction, erosion, or other causes and document any significant erosion by location with descriptions, drawings, and/or photographs. The Mapping Partner is not required to field survey transects unless available topographic data are unsuitable or incomplete.

The community, county, and state are usually the best sources for topographic data. The Mapping Partner shall examine USGS 7.5-minute series topographic maps. The USGS maps may have a 5-foot contour interval, and if not, they are still often useful as a reference for planimetric features in the study area.

**Table D-14. Elevations of Low Water Datum on the Great Lakes**

| LOCATION | LOW WATER DATUM ELEVATION: | |
|---|---|---|
| | FEET ABOVE IGLD85 | FEET ABOVE NGVD29 (APPROXIMATE) |
| Lake Superior | 601.1 | 601 |
| Lake Michigan | 577.5 | 578 |
| Lake Huron | 577.5 | 578 |
| Lake St. Clair | 572.3 | 573 |
| Lake Erie | 569.2 | 570 |
| Lake Ontario | 243.3 | 244 |

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### D.3.2.4 Land-Cover Data

The land-cover data include information on structures and vegetation. Stereoscopic aerial photographs can provide the required data on structures and some of the data on vegetation. The aerial photographs must not be more than 5 years old unless they are updated by surveys. A local, county, or State agency may have the coastline photographed on a periodic basis. That agency may provide the photographs or give permission to obtain them from its contractor. Because topographic maps are often developed from aerial photographs, the Mapping Partner also shall contact the mapping contractor for the topographic maps for data.

Aerial photographs can provide the required data on tree- and bush-type vegetation and can be used to identify areas although not the specific type of grass-like vegetation. National Wetland Inventory maps from the U.S. Fish and Wildlife Service and color infrared aerial photographs can provide more specific data required for marsh plants. Ground-level photographs and surveys also are useful in providing information on the plants (e.g., density, species). State offices of coastal zone management, park and wildlife management, and/or natural resources should be able to provide information on significant vegetation types. Also, the Mapping Partner shall contact local universities with coastal studies and/or Sea Grant programs. The Mapping Partner

may conduct field surveys in lieu of the above sources, but these are more cost effective when used only to verify some of the data obtained from these sources.

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### D.3.2.5 Bathymetric Data

It is not possible to provide precise guidance on the extent of bathymetry needed for a Great Lakes FIS. In some cases, only typical water depths in the vicinity of shore structures will be required in the analysis of wave effects. For sand beaches, bathymetry out to water depths of approximately 30 feet is required for wave treatments. Bathymetry further offshore may be useful for interpreting likely differences between nearshore and offshore wave conditions. (See Subsection D.3.2.6). An advisable procedure for studies of Great Lakes sites is to gather any readily available bathymetric data, but to defer all data reduction or analysis until the need is firmly established. Bathymetric data can be acquired from National Ocean Survey nautical charts, although any reliable source can be used.

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### D.3.2.6 Offshore Wave Characteristics

One basic assumption in conducting coastal wave analyses is that wave direction must have some onshore component, so wave hazards occur coincidentally with the 1-percent-annual-chance flood. That assumption appears generally appropriate on open coasts and bay shores of the Great Lakes, where the 1-percent-annual-chance SWEL must include some contribution from storm surge and usually requires an onshore wind component. However, the assumption of onshore waves along the shores of connecting channels, near inlets, and behind protective islands may require detailed examination.

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Once the Mapping Partner has confirmed that sizable waves travel onshore during the 1-percent-annual-chance flood, the most important specification is wave period rather than wave height. This is because wave heights are severely limited by shallow water at sites where the models described in Subsections D.3.5 and D.3.6 are applied. Wave treatments within those models provide depth-limited wave heights controlled by the wave period, so that the specified period influences the results of coastal wave analyses. The specified wave period can pertain to offshore storm waves in deep water, because dominant or spectral peak period is commonly unchanged during complex wave transformations near the shore. The most notable sources of suitable storm-wave information along Great Lakes coasts are the USACE Coastal Engineering Research Center (CERC) Wave Information Studies (WIS) Nos. 22, 23, 24, 25, and 26, with one report for each Great Lake on computed wave conditions in deep water from 1956 to 1987 (Driver, Reinhard, & Hubertz, 1991 and 1992; Hubertz, Driver, & Reinhard, 1991; Reinhard, Driver, & Hubertz, 1991). Maps locating approximately 300 sites for which computed wave information is available, one map for each lake, are included in Subsection D.3.9.

The draft of "Basic Analyses of Wave Action and Erosion with Extreme Floods on Great Lakes Shores" (Dewberry & Davis, 1995) concluded from historical evidence that extreme floods were

usually accompanied by the local 1/2-year wave condition on Lake Ontario, or by the 3-year wave condition on Lakes Erie, Huron, Michigan, and Superior. Those wave heights can be determined using the simple treatment illustrated by Figure D-36. Tabulated significant wave heights in the CERC WIS reports include the extremes for each month/year at every calculation site, and the median of each set of results gives the 2-month/2-year wave height. Extreme wave heights at various recurrence intervals usually are well approximated by an exponential distribution, so those two known values on a semi-logarithmic graph define other significant wave conditions of interest, as demonstrated in Figure D-36.

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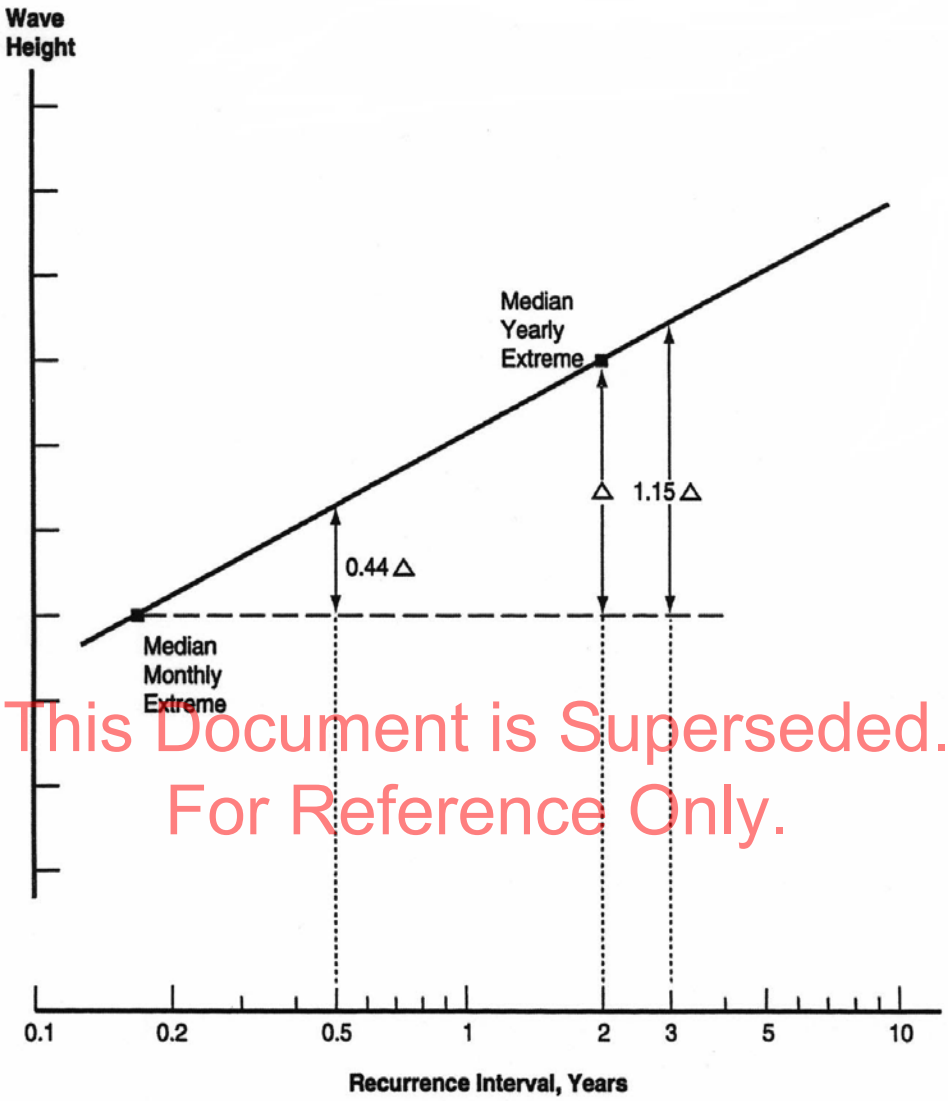


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**Figure D-36. Defining ½ Year or 3-Year Wave Height in an Exponential Distribution Using a Semi-Logarithmic Graph.**

Once a suitable offshore wave height is specified from the CERC WIS reports, the Mapping Partner shall determine the wave period crucial to coastal analyses in one of two ways. The more rigorous determination examines the electronic file of calculated conditions for 1956 to 1987, extracting cases with the specified wave height and with wave direction toward shore; prevalent wave period in those cases should be appropriate to the flood. Section D.3.9 includes examples of appropriate wave conditions derived for several sites on each of the Great Lakes. An alternative procedure considers wave steepness, or ratio of wave height to wavelength, with these typical values for storm waves: 0.035 for Lake Ontario or Lake Erie, 0.04 for Lake Huron or Lake Michigan, and 0.045 for Lake Superior. In deep water, the wavelength is 0.16 times the gravitational acceleration times the wave period squared, so specified wave steepness and wave height imply a suitable wave period for the site.

The hindcast wave study of the CERC WIS reports provides no information for Lake St. Clair, or within major embayments and connecting channels of the Great Lakes. Such sites require an independent assessment to define likely wave characteristics associated with the 1-percent-annual-chance flood. Fundamental information for such an assessment includes the water basin geometry at a site and the meteorology of storms potentially yielding the 1-percent-annual-chance SWEL, i.e., capable of generating the surge magnitude needed in addition to a high mean lake level.

Major factors in wave generation are windspeed and duration, local water depth, and fetch length. Fetch length is the over-water distance along which waves arise (USACE, 1984). In the Great Lakes vicinity, a windspeed of 40 mph sustained for several hours is usually appropriate to the 1-percent-annual-chance flood. For some cases, fetch length might be estimated as straight-line distance in the wind direction, but current guidance specified in the USACE ACES manual (USACE, 1992) pertinent to many Great Lakes sites indicates that a more involved analysis of restricted fetches must be performed for water basins of relatively complex geometry. The effective fetch length is derived as a weighted average of available distance with angle from the wind direction, as outlined in Figure D-37. A PC-compatible computer program included with the ACES manual is convenient for evaluating restricted fetch geometries and provides estimates of representative wave height and wave period based upon recommendations by CERC on wave generation.

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### D.3.2.7 Coastal Structures

Documentation gathered for each coastal structure that may provide protection from 1-percent-annual-chance flood hazards should include the following:

- Type and basic layout of structure;
- Dominant site particulars (e.g., local water depth, structure freeboard, ice climate); etc.
- Construction materials and present integrity;

•

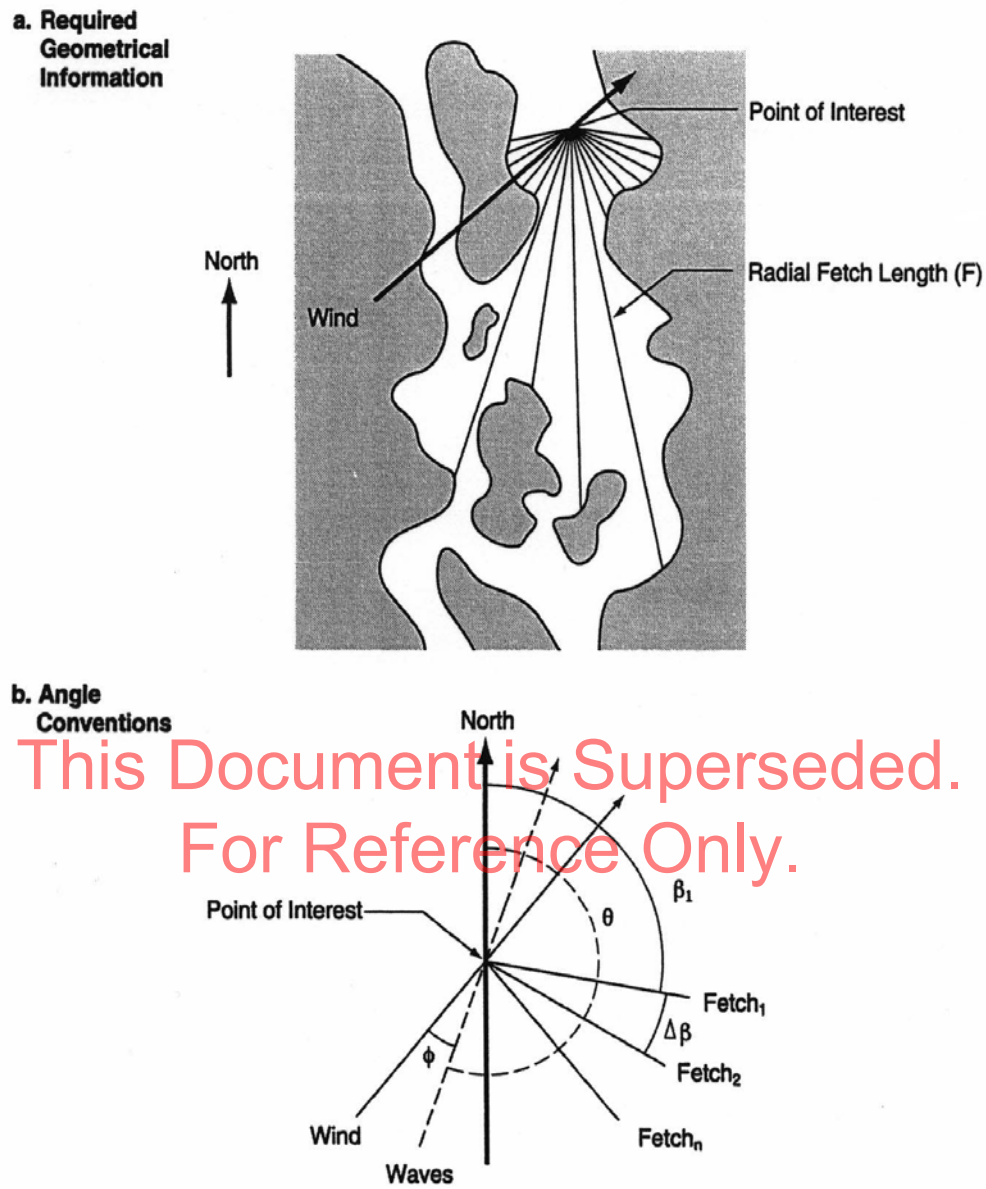


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**Figure D-37. Outline of Geometry for Wave Development on Restricted Fetches, from ACES Direction of Wave Development (θ) is Defined by Maximizing the Product $[(F_\phi)^{0.25} \cdot (\cos \phi)^{0.44}]$.**

- Historical record for structure, including construction date, maintenance plan, responsible party, and repairs after storm episodes; and
- Clear indications of effectiveness/ineffectiveness.

The Mapping Partner may develop much of this information through office activity, including a careful review of aerial photographs. In some cases of major coastal structures, site inspection could be advisable to confirm preliminary judgments.

[February 2002]

### D.3.2.8 Historical Erosion Accounts

Coastal erosion can occur during any major storm; however, the most significant erosion events for the purpose of a coastal FIS are those that occur with major storms during historical periods of high lake levels. Ideal information documenting storm-eroded cross sections will seldom be available because studies including repetitively surveyed profiles appear rare, except at some Lake Michigan sites. Although quantitative data may not be available, qualitative information can be valuable in confirming that reasonable results are obtained from the erosion assessment. The Mapping Partner shall conduct a search for erosion descriptions in newspaper articles or other publications, focusing on recent intervals of high mean lake levels. In addition, State agencies may be able to provide long-term recession rates over the study area. These are helpful in demonstrating local susceptibilities to storm-induced erosion.

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[February 2002]

### D.3.2.9 Historical Flood Information

Information from previous storms and floods can be valuable in developing proper assessments of coastal flood hazards. This is particularly true on the Great Lakes, because many notably extreme events occurred on the four western lakes during 1985, 1986, and 1987 and ample information should be readily available for many study sites.

General descriptions of flooding are useful in determining what areas are subject to flooding and in obtaining an understanding of flooding patterns. More specific information, such as erosion associated with the event or the location of buildings damaged by wave action, can be used to verify the results of the coastal analyses. When quantitative data on the effects, recorded water elevations, and offshore wave conditions are available, the Mapping Partner shall check those data for proximity to the coastal site and impact on the evaluation. Those data can be used to estimate recurrence intervals for SWEL and wave action during the event and assist in the appropriate comparison to the 1-percent-annual-chance flood conditions and SWELs established by the USACE for the specific recurrence intervals (1988).

Local, county, and State agencies are usually good sources for historical data, especially during the more recent events. It is becoming common practice for these agencies to record significant

flooding with photographs, maps, and/or surveys. Federal agencies such as the USACE, USGS, and NRC prepare post-storm reports for the more severe storms. Local libraries, newspapers, and historical societies may also be able to provide some useful data.

Additional criteria and submittal requirements for historical information are identified in the certification forms package for Study Contractors (SC-1) and the application/certification forms package (MT-2) for map revision requests.

[February 2002]

## D.3.3 Evaluation of Coastal Structures

The crucial first consideration in evaluating a coastal structure is whether it was properly designed and has been maintained to provide protection during the 1-percent-annual-chance flood. If it can be expected to survive the 1-percent-annual-chance flood, the structure should figure in all ensuing analyses of wave effects (erosion, runup, and wave height). Otherwise, it should be considered destroyed before the 1-percent-annual-chance flood and removed from subsequent transect representations.

The USACE technical report entitled *Criteria for Evaluating Coastal Flood-Protection Structures* (Walton, Ahrens, Truitt, & Dean, 1989) recommends specific criteria for evaluating coastal flood-protection structures in regard to the 1-percent-annual-chance flood. A FEMA memorandum dated April 23, 1990, entitled "Criteria for Evaluating Coastal Flood Protection Structures for National Flood Insurance Program Purposes," based on the USACE report, provides a self-contained account of the evaluation process. The criteria in the memorandum have been adopted as the basis for NFIP accreditation of new or proposed coastal structures to reduce the flood hazard areas and elevations designated on the current NFIP maps. Ideally, these evaluation criteria could be applied to existing coastal structures, but for older structures, design and construction information sufficient to complete the formal evaluation is typically unavailable. For these structures, engineering judgment based on visual inspection and any historical evidence should be used.

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In general, for evaluation of coastal structures on the Great Lakes the Mapping Partner shall rely on engineering judgment firmly based on experience regarding structural stability at sites with similar flood and wave climate. Because extreme floods have been relatively common over the past decade on the Great Lakes, the Mapping Partner shall consider historical information about a particular structure in its evaluation. Construction date and damage history of a structure permit a performance record to be accumulated for events potentially comparable to the 1-percent-annual-chance flood.

Analysis based on historical information and past performance may be complicated by one unique aspect of Great Lakes design considerations. The 1990 FEMA memorandum specifies that representative analyses be carried out at a range of water levels, usually from the Low Water Datum to the 1-percent-annual-chance SWEL for Great Lakes sites. However, incident wave conditions associated with the 1-percent-annual-chance flood may be markedly less extreme than those expected for lower but more persistent water levels near long-term Mean Lake Level.

Nevertheless, even where water depth at the structure site strongly limits local wave heights, the most severe conditions for design could still occur during the 1-percent-annual-chance flood; therefore, the Mapping Partner must consider these conditions.

The USACE technical report identifies the four primary functional types of coastal flood protection structures: gravity seawalls, pile-supported seawalls, anchored bulkheads, and dikes or levees. The report recommends as a general policy that "FEMA not consider anchored bulkheads for flood-protection credit because of extensive failures of anchored bulkheads during large storms" (p. 100). However, the report provides no examples for the Great Lakes. Seacoast storm conditions are possibly quite different from the 1-percent-annual-chance flood on the Great Lakes; therefore, this structure type cannot be completely discredited.

The FEMA memorandum focuses on structures designed for flood protection. Such structures can have a significant impact on the information shown on a FIRM, perhaps directly justifying the removal of sizable areas from the Coastal High Hazard Area. However, structures in other categories also are to be considered. Although a breakwater may act primarily to limit wave action, and a revetment primarily to control shore erosion, these structures also can provide 1-percent-annual-chance flood protection. The FEMA memorandum places the responsibility on local interests to certify new structures; however, it is crucial that the Mapping Partner evaluate the structure accurately and consider its effects. For example, a structure might decrease flood impacts in one area, yet increase erosion or wave hazards at adjacent sites. Of course, the greater the potential effects of a coastal structure, the more detailed the evaluation process should be.

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As discussed in Volume 2, additional requirements regarding coastal structures are included on Form 10 of the Application/Certification forms package (MT-2) for map revision requesters.

[February 2002]

## D.3.4 Erosion Assessment

Along many Great Lakes shores, erosion accompanying the 1-percent-annual-chance flood may change the location and alter the form of an existing sedimentary barrier extending above the local 1-percent-annual-chance SWEL. Mapping Partners must assess the likely erosion before proceeding to determination of additional flood effects dependent on topography, such as wave runup or overtopping, or overland wave heights. Procedures described here are meant to give schematic estimates of eroded transect geometry suitable for the purposes of a coastal FIS or map revision request on the Great Lakes.

In an erosion assessment relating to the 1-percent-annual-chance flood, Great Lakes coasts may be separated into three basic site categories:

1. Sandy shores with backing dunes or banks;

2. Backshore bluffs of cohesive material; and

3. Other shore situations more resistant to erosion during extreme floods, with bedrock, wetlands, shore protection, and other conditions.

For the third category, erosion is usually not too important a consideration, so the major distinction for present purposes is between sand dunes and cohesive bluffs. Besides up-to-date coastal topography, information about the basic shore type is crucial for an appropriate erosion assessment pertaining to the 1-percent-annual-chance flood. Also, documented erosion effects during a historical flood at the study site can be useful in a valid assessment of 1-percent-annual-chance flood effects, but such evidence requires careful interpretation, as discussed below.

Detailed examination of recent record episodes of lake levels (Dewberry & Davis, 1995) provides several notable findings:

- Extreme Great Lakes floods usually involve rather moderate storms during relatively brief intervals when mean lake level is significantly higher than the long-term average.

- The storm situation for an extreme flood on Lake Ontario is markedly different than on Lake Erie, Lake Huron, Lake Michigan, Lake Superior.

- Coastal erosion on the Great Lakes exhibits extreme geographical and temporal variability during intervals of high mean lake level.

Quantitative analysis establishes that Great Lakes erosion cross sections expected during the 1-percent-annual-chance flood are 270 square feet on Lake Erie, Lake Huron, Lake Michigan, and Lake Superior and 190 square feet on Lake Ontario.

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These amounts refer to the flood episode alone and lie entirely above the local 1-percent-annual-chance SWEL. The stated results derive from Great Lakes verification of an analysis similar to that which was performed for Atlantic Ocean and Gulf of Mexico regions for the 540-square-feet erosion cross section in seacoast 1-percent-annual-chance floods. Appropriate application of this erosion guidance can depend on basic type of shore morphology, as illustrated in Figures D-38 (bluff) and D-39 (sand dune).

The cases consider no shore features lakeward of the basic flood barrier, because any distinct topography presumably will be removed by storm erosion before the peak effects to be considered. For the bluff case in Figure D-38, erosion projection is based on a retreated profile parallel to the existing bluff, but with a potential adjustment to the eroded face governed by soil stability considerations for the site. For the dune case in Figure D-39, erosion projection makes use of an escarpment slope of 45°, corresponding to the usual duneface geometry for storm conditions. In each case, the barrier is presumed to be appreciably more sizable than the specified erosion cross section, even though that usually is more appropriate for bluff erosion where the barrier in effect is unlimited. Erosion analysis may be unnecessary for very large coastal dunes, extending 20 feet or more above the SWEL; such sand accumulations may be considered resistant to notable storm erosion and to wave overtopping on the Great Lakes.

These quite simplified depictions of eroded profile geometry for Great Lakes shores may require modification in accordance with site-specific factors, engineering judgment, or the more detailed erosion considerations usually appropriate on seacoasts (FEMA, 1995). Comparison of present assessment results to historical effects for notable local floods must recognize the extreme variability evident in Great Lakes shore erosion during a given storm. Documented large or small amounts of erosion during a notable historical storm or flood at a particular Great Lakes site do not imply that similar effects should be expected for the 1-percent-annual-chance

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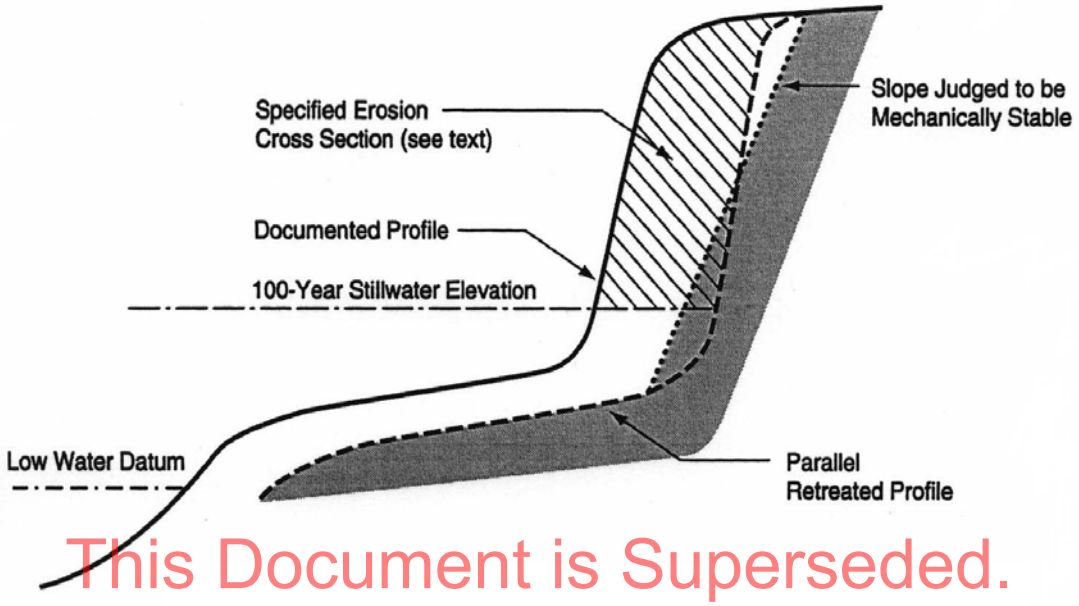


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**Figure D-38. Basic Erosion Considerations for Coastal Bluff Provides Shaded Shore Profile for Great Lakes Base Flood.**

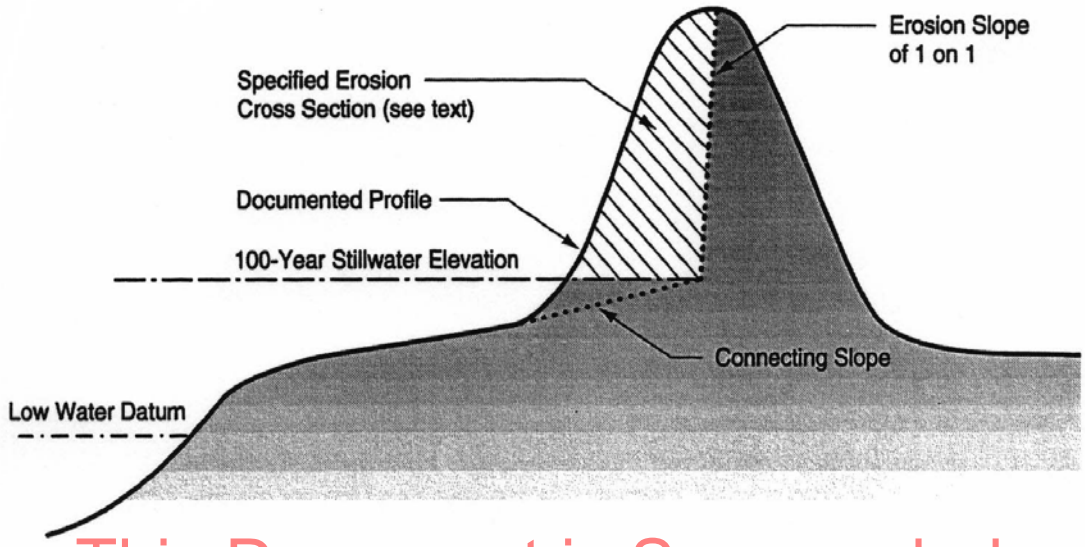


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**Figure D-39. Basic Erosion Considerations for Coastal Sand Dune Provides Shaded Shore Profile for Great Lakes Base Flood.**

flood. The only appropriate conclusion to be based directly on historical effects is that if a Great Lakes site has experienced no erosion over the past ten years, one should not assume that erosion will accompany the 1-percent-annual-chance flood.

The present evaluation guidelines outlined in Figures D-38 and D-39 lead to appropriate flood hazard identification, given that sizable wave effects on Great Lakes shores seldom penetrate inland past an erodible flood barrier in accordance with the geometrical consideration outlined in Figure D-40. In a Great Lakes FIS, the major result of an erosion assessment is a barrier profile both convenient and appropriate for ensuing wave analyses.

[February 2002]

## D.3.5 Wave Runup and Overtopping

Wave runup and overtopping constitute coastal hazards beyond those associated with stillwater coastal flooding and incident wave geometry. Wave runup is the uprush of water on a shore barrier intercepting the stillwater level. The water wedge both thins and slows during its excursion up the barrier, as residual momentum from wave motion near the shore is fully dissipated. The most significant characteristic of this process for present purposes is wave runup elevation: the vertical height above stillwater level ultimately attained by the extremity of uprushing water. Likely runup must be assessed for wave conditions expected to accompany the 1-percent-annual-chance flood. The extent of runup can vary greatly from wave to wave in storm conditions, so that a wide distribution of wave runup elevations provides the precise description of a specific situation. Wave overtopping occurs when an individual runup impulse surpasses the barrier crest and flood water penetrates inland of the shore barrier, perhaps with wave-like effects or with ponding of the flood waters behind the barrier.

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Current NFIP policy is that the mean runup elevation (rather than some occasional extreme) for a situation is appropriate in mapping coastal hazards of the 1-percent-annual-chance flood. The FEMA Great Lakes Wave Runup Model (GLWRM), which is based on methodologies recommended by the USACE, Detroit District, can be used to compute the mean runup elevation, as discussed in Subsection D.3.5.1. Although the GLWRM provides an entirely suitable runup elevation, it can treat only the three types of shore situation judged to be most frequently encountered on the Great Lakes. Therefore, adjustment or modification to computed results may be needed in applications at some sites. Section D.3.5.2 introduces some methods for extending the applicability of the GLWRM and also discusses other considerations potentially important for a Great Lakes coastal flood hazard evaluation.

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### D.3.5.1 Use of Great Lakes Wave Runup Model

The runup analysis begins with the determination of significant wave conditions near the shore. The site must be categorized as one of three shore types typical of the Great Lakes: smooth vertical wall, rip-rap revetment having a single face slope, or sloping sand beach. For a revetment or beach, the characteristic slope, considered the grade of the slope from the mean

lake

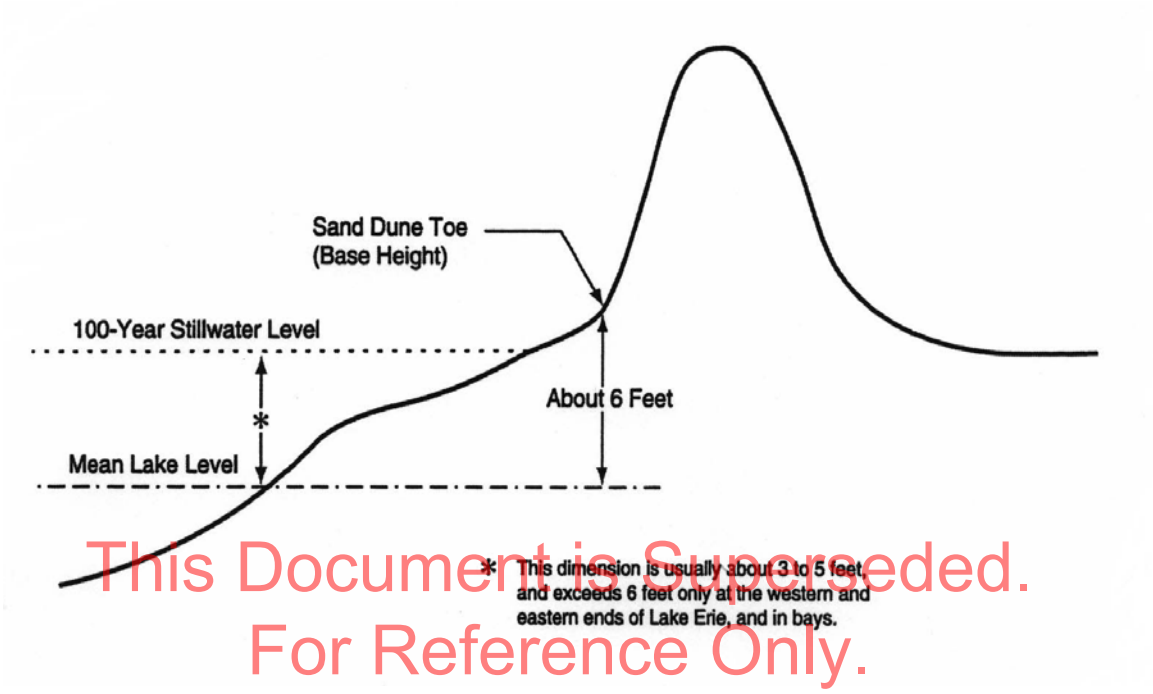


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**Figure D-40. Typical Great Lakes Coastal Geometry Prevents Wave Penetration Inland of Eroded Dune Site in Base Flood.**

level up to the 1-percent-annual-chance SWEL, must be determined. For a vertical structure or a sloping revetment, the wave conditions must be determined at the specified water depth of the structure toe and at a water depth of 26 feet for a sand beach. The depths to be used in analyzing wave conditions should be the depths of water below the local 1-percent-annual-chance flood level.

The wave runup elevation for the shore barrier can be estimated using the GLWRM, which is available from FEMA in digital format. The program executes step-by-step procedures for runup computation at Great Lakes sites, following the recommendations from the *Great Lakes Wave Runup Methodology Study* (USACE, June 1989). The interactive format occasionally prompts the user for input or review of hydraulic and topographic descriptions of a site, including the shore barrier specification, the 1-percent-annual-chance SWEL (see Subsection D.3.2.1), and offshore storm-wave characteristics (see Subsection D.3.2.6).

Tables D-15, D16, and D-17 present examples of computation input and output for the three distinct situations, namely, a vertical structure, a sloping revetment, and a sand beach.

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**Table D-15. Final GLWRM Results for Wave Runup on Vertical Structure. Diamonds Added to Identify Lines with Site Specific Specifications Input or Confirmed in Response to Interactive Screen Prompts.**

```
                wave runup on ◆ vertical wall
      1% annual chance flood ◆ 582.6 feet
          water depth at toe ◆   5.5 feet
       3-year wave period  T ◆   9.1
                          T':    2.6
                           L:  121.01
3-year deep water wave     H ◆  20.0 feet
                           K:    5.5
                       alpha:    0.0180
                         Hmo:    3.3
                       d bar:    0.0021
                     epsilon:    0.0068
                     Hs/Hmo ◆    0.907
            Hs at structure:     3.3
                        d/Lo:    0.0130
                     H/Ho' ◆     1.3500
                         Ho':    2.4
              Ho'/(gT**2):       0.00090
                   ds/Ho':       2.3
                 runup/Ho':      2.58
      vertical wall runup:       6.2
          runup elevation:     588.8 feet
```

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**Table D-16. Final GLWRM Results for Wave Runup on Sloping Revetment. Diamonds Added to Identify Lines with Site Specific Specifications Input or Confirmed in Response to Interactive Screen Prompts.**

```
                wave runup on◆  revetment
   1% annual chance flood◆ 581.6 feet
       water depth at toe◆   4.5 feet
    3-year wave period  T◆   9.1
                       T':   2.4
                        L:  109.45
3-year deep water wave  H◆  20.0 feet
                        K:   6.1
                    alpha:   0.0189
                      Hmo:   2.7
                    d bar:   0.0017
                  epsilon:   0.0062
                   Hs/Hmo◆   0.920
          H at structure:    2.7
              tan(theta)◆    0.22500
revetment (Greek ltr) xi:    2.8
        revetment runup:     3.4
      runup elevation: 585.0 feet
```

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**Table D-17. Final GLWRM Results for Wave Runup onto Sand Beach. Diamonds Added to Identify Lines with Site Specific Specifications Input or Confirmed in Response to Interactive Screen Prompts**

```
                wave runup on◆  beach
     1% annual chance flood◆ 582.6 feet
         water depth at toe:  26.0 feet
      3-year wave period  T◆   9.1
                         T':   5.7
                          L: 263.09
3-year deep water wave  H◆  20.0 feet
                          K:   2.6
                      alpha:   0.0125
                        Hmo:   9.4
                      d bar:   0.0098
                    epsilon:   0.0089
                   Hs/Hmo◆   1.084
          Hs in deep water:  10.2
              beach slope◆   0.17300
   beach (Greek ltr) xi:     1.115
                beach runup:  11.0
           runup elevation: 593.6 feet
```

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### D.3.5.2 Additional Considerations

As mentioned earlier in this Appendix, the GLWRM treats three shore configurations: smooth vertical wall, rip-rap revetment having a single face slope, or sloping sand beach. For some studies, the Mapping Partner may be required to evaluate other shore situations (e.g., grass or gravel shore slopes, mounds formed of other material or with a compound front slope). Although other methods and models for determining wave runup elevations could be used (see USACE, 1984 and 1992; Dewberry & Davis, 1991), the GLWRM runups can be adjusted to analyze these other shore situations. Using the GLWRM will provide consistency of results within a single study.

One parameter frequently used in NFIP coastal assessments is a roughness coefficient measuring barrier surface effects along the runup excursion (Dewberry & Davis, 1995; Stone & Webster, 1981). Table D-18 presents typical values of the roughness coefficient, usually designated as r, for common barrier materials. Wave runup elevation is assumed to vary directly with roughness coefficient, given no other difference in the geometrical configuration. Thus, GLWRM results for a sand beach (having a situation otherwise identical to that shown in Table D-13) may be multiplied by 0.90 to apply with grass, or by 0.70 to apply with gravel. For relatively steep slopes common to manmade shore structures, GLWRM results for a rip-rap revetment might be adjusted for application with other construction materials, using the appropriate ratio between roughness coefficients. Expressed formally, the runup on a rough surface is given as r times runup for a smooth surface, so that for rip-rap

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$$R_1 = r_1 R \tag{1}$$

and for some other rough barrier material

$$R_o = r_o R = r_o R_1/r_1 \tag{2}$$

where the value $R_1$ is obtained directly from the GLWRM.

Another simplification long employed in NFIP coastal assessments is the composite-slope method (Saville, 1958), where a hypothetical uniform slope is taken to represent the segmented barrier profile (Figure D-41). That equivalent slope customarily extends from the water depth with initial wave breaking to the limit of wave runup, or from a water depth equal to incident wave height when waves do not break (at a very steep shore). For a man-made structure, the GLWRM assumes a clearly identifiable toe or seaward limit to the wave barrier, so it is appropriate to start the equivalent uniform slope at that point. Because the landward limit assumed for the uniform slope is at the runup limit, some manual computation may be needed in iterative adjustment of the input slope to attain suitable consistency with calculated runup elevation.

**Table D-18. Appropriate Values for Roughness Coefficient in Wave Runup Calculations**

| ROUGHNESS COEFFICIENT | DESCRIPTION OF BARRIER SURFACE |
|---|---|
| 1.00 | Sand; smooth rock, concrete, asphalt, wood, fiberglass |
| 0.95 | Tightly set paving blocks with little relief |
| 0.90 | Turf, closely set stones, slabs, blocks |
| 0.85 | Paving blocks with sizable permeability or relief |
| 0.80 | Steps; one stone layer over impermeable base; stones set in cement |
| 0.70 | Coarse gravel; gabions filled with stone |
| 0.65 | Rounded stones, or stones over impermeable base |
| 0.60 | Randomly placed stones, two thick on permeable base |
| 0.50 | Cast-concrete armor units: cubes, dolos, quadripods, tetrapods, tribars, etc. |

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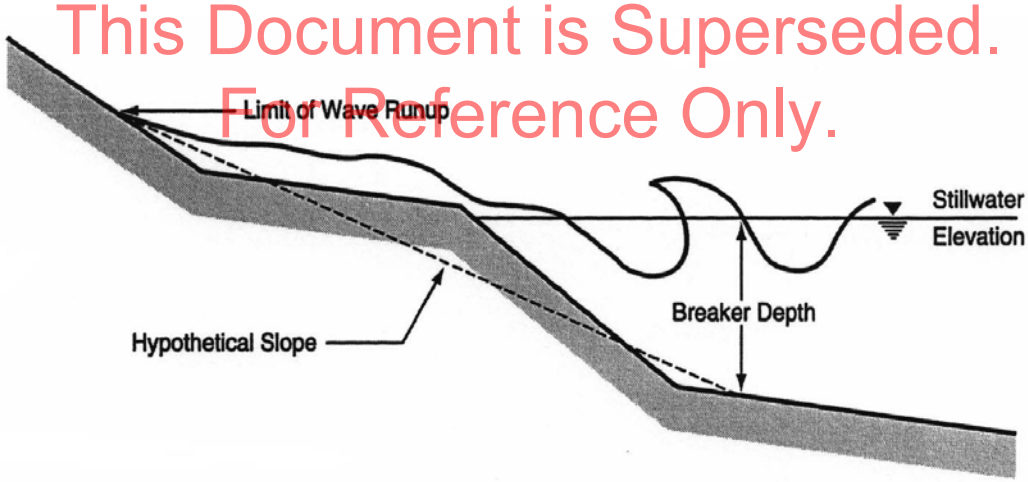


**Figure D-41. Hypothetical Slope for Determining Wave Runup on Composite Profiles.**

Once a definite runup elevation has been obtained for the shore situation, the Mapping Partner must compare it with barrier crest elevation to assess the possibility of wave overtopping. The examination takes into account that calculated runup elevation refers to common rather than extreme water excursions on the barrier, whereas all expected hazards of the 1-percent-annual-chance flood must be projected. If wave runup elevation reaches more than halfway from the stillwater level to the barrier crest, the Mapping Partner shall perform an overtopping assessment for flood hazards because likely wave runups occasionally will proceed over the shore barrier. Overtopping discharges in storm conditions may be estimated using empirical results in *Random Seas and Design of Maritime Structures* (Goda, 1985) for vertical walls, in "Design of Seawalls Allowing for Wave Overtopping" (Hydraulics Research Station, 1980) for sloping structures, and in "Wave Runup and Overtopping at Dunes during Extreme Storm Surge" (Delft Hydraulics Laboratory, 1983) for sand dunes with common erosion geometry. The Mapping Partner shall evaluate the effects of the discharge in terms of potential wave impacts, runoff depths, or ponding areas on ground landward of the shore barrier.

A distinct type of overflow situation can occur at low bluffs or banks backed by a nearly level plateau, where calculated wave runup may appreciably exceed the top elevation of the steep barrier. A memorandum entitled "Special Computation Procedure Developed for Wave Runup Analysis for Casco Bay, FIS - Maine, 9700-153" provides a simple procedure to determine realistic runup elevations for such situations, as illustrated in Figure D-42 (French, 1982). An extension to the bluff face slope permits computation of a hypothetical runup elevation for the barrier, with the imaginary portion given by the excess height $R' = (R\text{-}C)$ between calculated runup and the bluff crest. Using that height $R'$ and the plateau slope $m$, Figure D-43 defines the inland limit to wave runup, $X$, corresponding to runup above the bluff crest of ($mX$) or an adjusted runup elevation of $R_a = (C + mX)$. This procedure is based on a Manning's "n" value of 0.04 with some simplifications in the energy grade line and is meant for application only with positive slopes landward of the bluff crest. A different treatment of wave overflow onto a level plateau, for possible FIS usage, is provided in "Overland Bore Propagation Due to an Overtopping Wave" (Cox & Machemehl, 1986).

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A less common situation on the Great Lakes is that calculated wave runup exceeds a relatively high barrier crest backed by negative slopes. In such cases, a general rule limits the appropriate runup elevation to 3 feet above maximum ground elevation. Floodwaters overtopping the barrier percolate into the bed, or run along the back slope until encountering another flooding source or a ponding area. A runoff area is usually designated as Zone AO, with depth of flooding of 1, 2, or 3 feet; a ponding area may be designated as Zone AH, with a flood elevation. Standardized NFIP procedures have been developed for the treatment of sizable runoff and ponding, but are beyond the scope of this presentation; see *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping* (FEMA, 1995).

Aside from these considerations relating to the inland limit of flooding from wave runup and overtopping, the Mapping Partner must integrate the runup elevation at the shore barrier with calculated wave crest elevations near the shore.

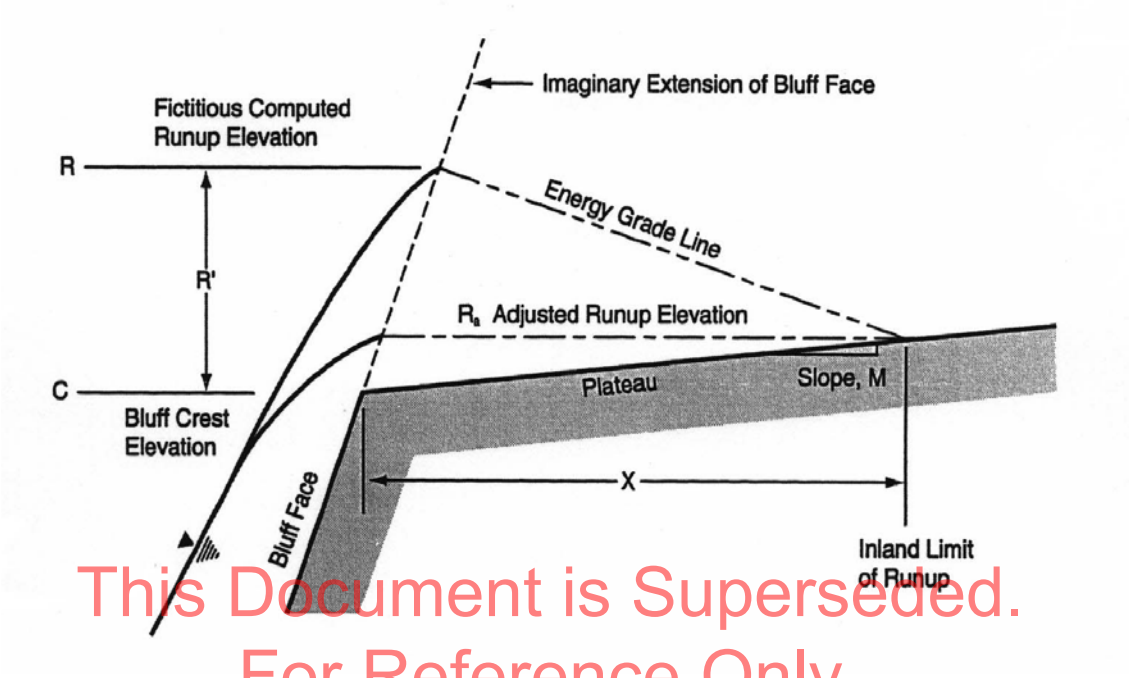


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**Figure D-42. Treatment of Wave Runup onto Plateau above Low Bluff.**

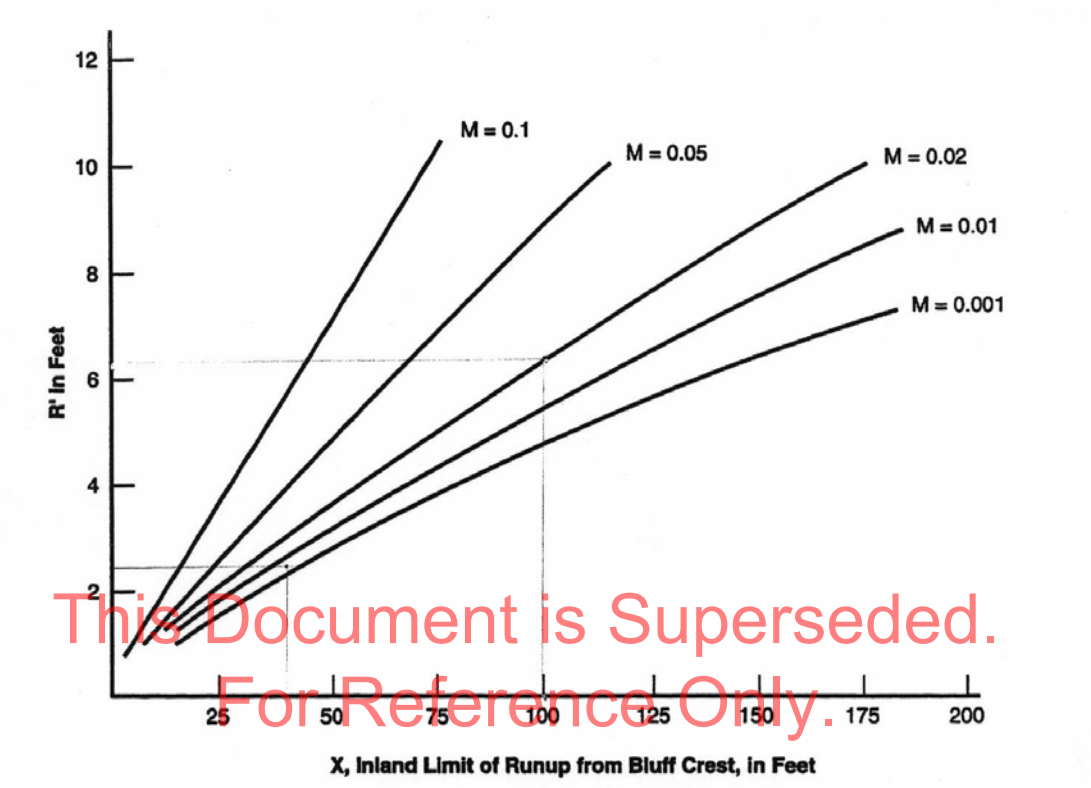


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**Figure D-43. Computation of Wave Runup for Low Bluffs.**

## D.3.6 Nearshore Wave Dimensions

As waves propagate near the shore and over a flooded area, they undergo transformations caused by local winds, interaction with the bottom, and physical features such as buildings, trees, or marsh grass. Figure D-44 illustrates the effects at a transect of obstructions on the wave crest elevations and the flood zone. For Great Lakes coasts, the effects must be calculated objectively along each transect, from the Low Water Datum to the flooding limit. Fundamental analysis of wave effects for an FIS is provided by the FEMA computer program Wave Height Analysis for Flood Insurance Studies (WHAFIS). The program calculates wave heights, wave crest elevations, flood hazard zone designations, and the location of zone boundaries along a transect. The current program version for the Great Lakes region, WHAFIS 3.0 GL, incorporates windspeeds appropriate to Great Lakes events (40 mph over fully exposed waters and 30 mph for inland waters or marsh).

Wave description for an FIS addresses the controlling wave height, equal to 1.6 times the significant wave height common as a basic wave description, with the dominant (or spectral peak) wave period. Significant wave height is the average height of the highest one-third of waves, and controlling wave height is slightly less than average height of the highest one percent of waves in storm conditions. The wave condition of interest is that expected to accompany the 1-percent-annual-chance flood.

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Within WHAFIS, a wave action conservation equation governs wave regeneration caused by wind and wave dissipation caused by marsh plants. This equation is supplemented by the conservation of waves equation, which expresses the spatial variation of the wave period at the peak of the wave spectrum. The wave energy (i.e., wave height) and wave period respond to changes in wind conditions, water depths, and obstructions as a wave propagates. These equations are solved as a function of distance along the transect. Technical details are fully documented in the WHAFIS program documentation (FEMA, September 1988).

The current NFIP treatment of wave dimensions has resulted from periodic upgrades of technical procedures, with the original basis being the NAS methodology documented in *Methodology for Calculating Wave Action Effects Associated with Storm Surges* (NAS, 1977). The NAS methodology, which was developed to be suitable for manual computations, accounts for varying fetch lengths, barriers to wave transmission, and the regeneration of waves over flooded land areas. Several aspects of usual Great Lakes situations suggest that simplified analysis, considering only water depth and thin vertical barriers, might give a useful outline of wave effects for some sites.

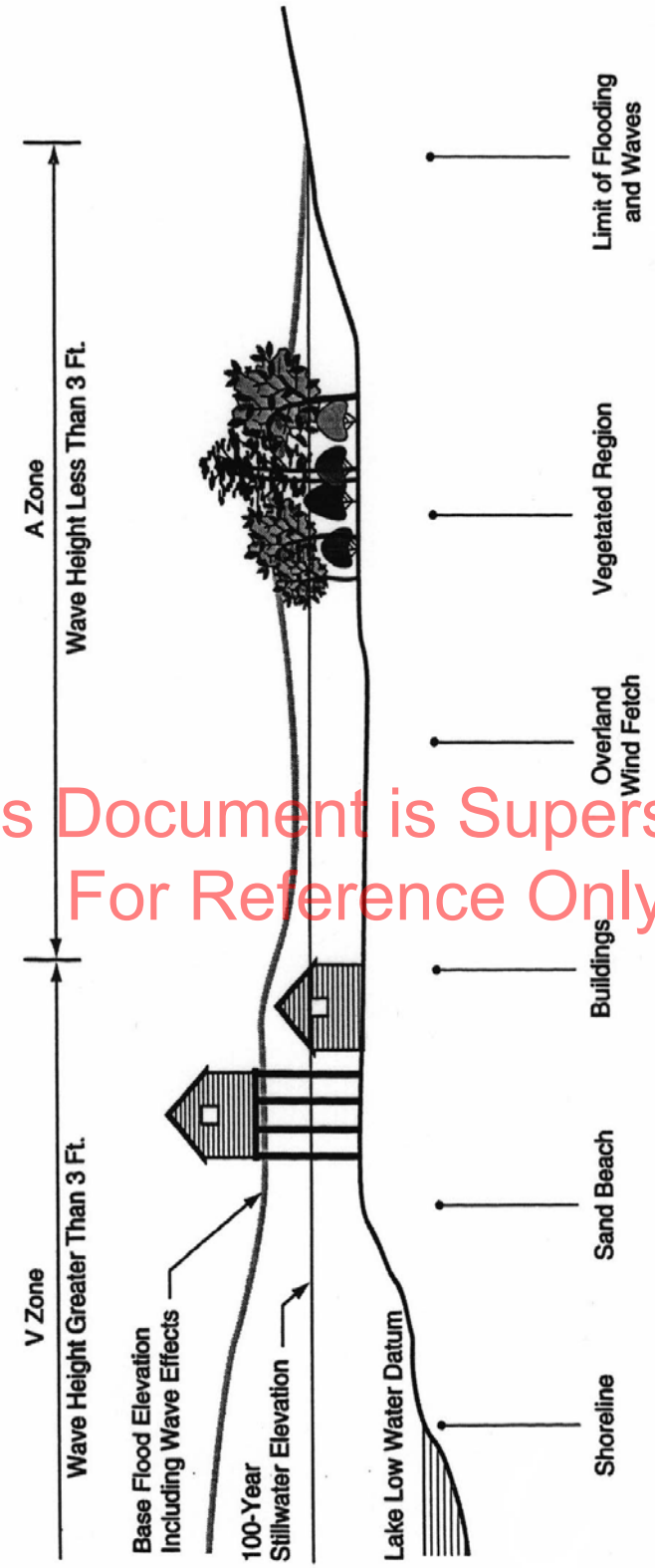


**Figure D-44. Schematic Wave Effects along a Coastal Transect.**

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### D.3.6.1 Simplified Wave Height Analysis

The potential usefulness of the simplified wave analysis method for treating 1-percent-annual-chance flood waves is suggested by certain aspects of the Great Lakes situation: the relatively low windspeeds, reducing the intensity of wave regeneration; the relatively simple eroded geometries, which are generally featureless lakeward of the ultimate flood barrier; the absence of barrier islands and back bays so that another flood source or elevation is seldom encountered; and the typical narrowness of the Coastal High Hazard Area. This method would not be appropriate where the transect includes coastal wetlands, other land cover providing appreciable flow resistance, or an extensive lowland area liable to flooding. Before any wave analysis, there must be confirmation that sizable waves likely propagate towards shore during the local 1-percent-annual-chance flood.

All elements of this treatment are extracted from the basic NAS methodology (Dawdy & Maloney, 980; FEMA, February 1981; NAS, 1977), with wave heights entirely regulated by local water depth. The estimated flood elevation (Z) is defined by wave action accompanying the flood, with the majority of the waveform in the crest above the 1-percent-annual-chance SWEL (S):

$$Z = S + 0.7\ H \tag{3}$$

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where H is the local controlling wave height. A bound to H is given by wave breaking in shallow water, with the upper limit

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$$H_* = 0.78\ d \tag{4}$$

where local water depth (d) equals (S-G), G being ground elevation. Combining these relations, local ground elevation constrains the flood elevation to an upper limit of

$$Z_* = S + 0.55\ d \tag{5}$$

Equation (4) implies that a minimum water depth of 3.85 feet is required for the 3-foot wave height characterizing a V Zone.

An obstruction on the transect may conveniently be treated as a thin barrier if flooding occurs to the same S on each side. Wave transmission is assumed to occur only if the barrier top elevation (C) is below S plus one-half the incident wave height ($H_i$). Transmitted wave height is

$$H_t = 0.5\ H_i + B \tag{6}$$

where B = ½[0.78 (S-C)] if the barrier is submerged, but B=[(S-C)] otherwise; the upper limit of $H_t = H_i$ occurs when $H_i$ is less than [0.78 (S-C)], requiring that $H_i$ is not depth-limited. Transmitted wave height beyond the barrier remains limited by ground elevation on the landward side of the barrier ($G_t$), through Equation (2), just as incident wave height is limited by

ground elevation on the lakeward side ($G_i$). With engineering judgment, wave obstructions other than walls might be represented by proper choices of $G_i$, C, and $G_t$ in this procedure.

Figure D-45 presents an idealized numerical example demonstrating estimated wave heights, flood elevations, and flood zones. Note that varying elevations of depth-limited wave crests mirror the ground slopes.

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### D.3.6.2 Use of WHAFIS 3.0 GL Model

Careful preparation and input of required site data are necessary in using WHAFIS. Like the other coastal treatments, the WHAFIS model considers the study area by representative transects. For WHAFIS, transects must be defined considering major topographic, vegetative, and cultural features. The transect, referenced to NGVD29, begins at the local elevation of Low Water Datum (Table D-13) and proceeds landward until either the ground elevation exceeds the SWEL or another flooding source is encountered.

Fundamental specifications for WHAFIS input include the 1-percent-annual-chance flood SWEL and a description of waves existing at the transect start. The wave description provides for an overwater fetch length, an initial significant wave height, or an initial period of dominant waves. In most Great Lakes applications, the wave period should be the input description, because that parameter is readily available from information about offshore waves (see Subsection D.3.2.6).

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The Mapping Partner shall locate transects on the work maps and plot the transect ground profile from the topographic data, adjusted for erosion. The Mapping Partner shall ensure that each transect has all the input data identified on the profile plot for ease of input coding. The Mapping Partner also shall identify the location, height, and width of elongated manmade structures and show them as part of the ground profile, after confirming the structure's stability under forces of the 1-percent-annual-chance flood (see Subsection D.3.3).

Buildings are specified on the transect as rows perpendicular to the transect. Because buildings are not always situated in perfect rows, the Mapping Partner shall exercise judgment to determine which buildings can be represented by a single row. The required input value for each row of buildings is the ratio of open space to total space. This is simply the sum of distances between buildings in a row, divided by the total length of that row.

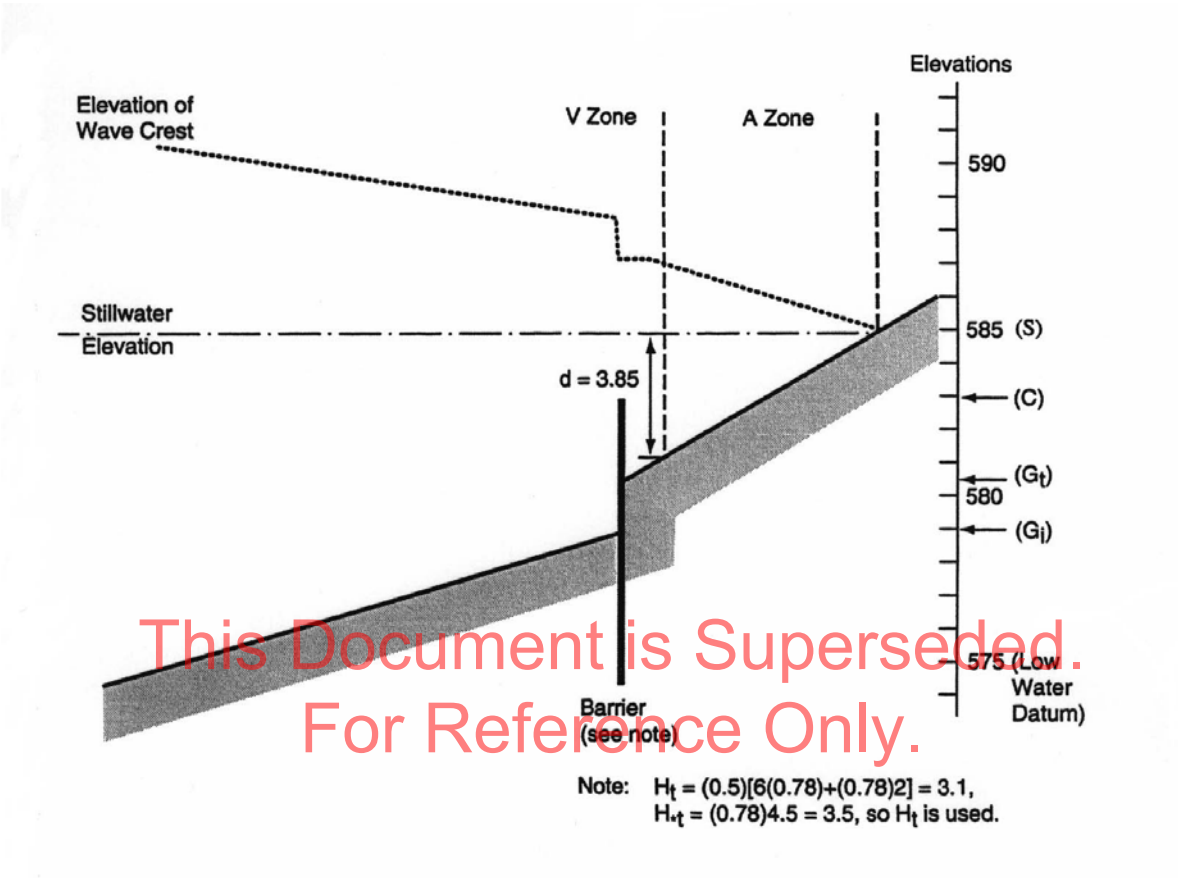


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**Figure D-45. Schematic Example of Simplified Wave Height Analysis Regulated by Local Water Depth, with All Indicated Quantities in Feet.**

The first row or two of buildings along the shoreline is not always to be considered as obstructions. During a 1-percent-annual-chance flood, it is sometimes appropriate to assume that if they are not elevated on pilings, these buildings will be destroyed before the peak of the flood occurs. If they are elevated, the waves should propagate under the structures with minimal reduction in height. The Mapping Partner shall contact local officials to obtain typical construction methods and the lowest elevations of structure.

The WHAFIS program has two routines for vegetation: one for rigid vegetation that can be represented by an equivalent "stand" of equally spaced circular cylinders (NAS, 1977) and one for marsh vegetation that is flexible and oscillates with wave action (FEMA, 1984). For either type, considerable care is required in selecting representative parameters and in ruling out that the vegetation will be intentionally removed or that effects during a storm would be markedly reduced through erosion, uprooting, or breakage.

For the areas of rigid vegetation located on the transect, the required input values are the drag coefficient, CD; mean wetted height, h; mean effective diameter, D; and mean horizontal spacing, b. The value of CD should vary between 0.35 and 1.0, with 1.0 being used in most cases of wide vegetated areas. When the vegetation is in a single stand, a value of 0.35 should be used. Representative values for h, D, and b can be obtained from stereoscopic aerial photographs or by field surveys. Various guides for terrain analysis can provide procedures for estimating these values from aerial photographs. Table D-19 provide a useful procedure developed from Terrain Analysis Procedural Guide for Vegetation (Messmore, Vogel, & Pearson, 1979).

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For marsh vegetation, a more complicated specification is required for completeness, and the eight parameters used to describe the attenuation properties of a specific vegetation type are explained in Table D-20.

WHAFIS includes considerable basic information on eight common types of seacoast marsh plants listed in Table D-21 (FEMA, 1984; FEMA, 1989), but among these, apparently only the *Juncus* species are likely to occur in the freshwater marshes on the Great Lakes. For vegetation not listed in Table D-21, the Mapping Partner shall input the geometrical parameters to WHAFIS.

At lakeshore elevations that are seldom flooded and thus are important for the 1-percent-annual-chance flood, a great diversity of wetland vegetation can occur along with upland vegetation species. Prevalent marsh plants at relatively high elevations (Levels Reference Study Board) may include combinations of grasses (*Phalaris arundinacea*, *Calamagrostis canadensis*), sedges (*Carex lacustris*, *C. rostrata*, *C. stricta*, *C. lasiocarpa*), rushes (*Juncus canadensis*, *J. effusus*), or cattails (*Typha* varieties). The Mapping Partner shall specify each existing type of vegetation s, along with its fractional coverage in any sizable patch; a patch of at least 10,000 square feet (0.09 hectare) can affect wave heights appreciably.

**Table D-19. Procedure for Vegetation Analysis Using Stereoscopic Aerial Photographs.**

1. Using the parallax bar or wedge, determine the height of three representative trees and compute the average height, h.

2. Locate three representative tree crowns, measure the diameters, and compute the average crown diameter, CD.

3. Determine the type of vegetation and calculate the stem diameter, D, using the following formulae:

   Southern Pines — D (inches) = 5 + 0.5 CD (feet)

   Eastern Hardwoods,
   Northern Pines and Others — D (inches) = 0.75 CD (feet)

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4. Based on the scale of the aerial photographs, determine the diameter of a circle containing 0.08 hectares using Table 4. Place the circle on the photograph, over a representative area of trees, and count the number of trees, n, in the circle. A magnifier may be needed. More than one area can be counted and an average used for n. Calculate the number of trees per hectare, N, using the following formula:

$$N = \frac{n}{0.08}$$

5. Determine the horizontal spacing between trees using the following formula:

$$b \text{ (feet)} = 3.28 \left( \frac{12732}{N} \right) - \frac{D \text{ (inches)}}{12}$$

**Table D-19. Procedure for Vegetation Analysis Using Stereoscopic Aerial Photographs (Cont.)**

CIRCLE DIAMETERS
.08 HECTARE AREA, (1/5 ACRE)
(800 Square Meters, 8712 Square Feet)

| PHOTO SCALE | .08 HECTARE CIRCLE | CIRCLE DIAMETER INCHES | CIRCLE DIAMETER MILLIMETERS |
|---|---|---|---|
| 1:5,000 | | .253 | 6.38 |
| 1:6,000 | | .211 | 5.32 |
| 1:7,000 | | .1805 | 4.56 |
| 1:8,000 | | .158 | 3.99 |
| 1:9,000 | | .140 | 3.55 |
| 1:10,000 | | .126 | 3.192 |
| 1:11,000 | | .115 | 2.90 |
| 1:12,000 | | .105 | 2.66 |
| 1:13,000 | | .092 | 2.46 |
| 1:14,000 | | .090 | 2.28 |
| 1:15,000 | | .084 | 2.13 |
| 1:16,000 | | .079 | 1.99 |
| 1:17,000 | | .074 | 1.88 |
| 1:18,000 | | .070 | 1.77 |
| 1:19,000 | | .067 | 1.68 |
| 1:20,000 | | .063 | 1.60 |
| 1:21,000 | | .060 | 1.52 |
| 1:22,000 | | .057 | 1.45 |
| 1:23,000 | | .055 | 1.39 |
| 1:24,000 | | .053 | 1.33 |
| 1:25,000 | | .051 | 1.28 |

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**Table D-20. Marsh Plant Parameters**

| PARAMETER | EXPLANATION |
|---|---|
| $C_D$ | Effective drag coefficient. Includes effects of plant flexure and modification of the flow velocity distribution. Default value is 0.1, usually appropriate for marsh plants without strong evidence to the contrary. |
| $F_{cov}$ | Fraction of coverage. A default value is calculated by the program so that each plant type in the transect is represented equally, and the sum of the coverage for the plant types is equal to 1.0. |
| h | Unflexed stem height (feet). The stem height does not include the flowering head of the plant, the inflorescence. |
| N | Number density. Expressed as plants per square foot. The relationship to the average spacing between plants, b, can be expressed as $N = 1/b^2$. |
| $D_1$ | Base stem diameter (inches). Default value may be determined from stem height and regression equations built into the program. |
| $D_2$ | Mid stem diameter (inches). Default value may be determined from plant type and base stem diameter. |
| $D_3$ | Top stem diameter (inches), at the base of the inflorescence. Default value may be determined from plant type and base stem diameter. |
| $CA_b$ | Ratio of the total frontal area of the cylindrical portion of the leaves to the frontal area of the stem below the inflorescence. Default value may be determined from the plant type. |

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**Table D-21. Abbreviations of Marsh Plant Types Used in WHAFIS**

| SPECIES OR SUBSPECIES | ABBREVIATION |
|---|---|
| *Cladium jamaicense* (saw grass) | CLAD |
| *Distichlis spicata* (salt grass) | DIST |
| *Juncus gerardi* (black grass) | JUNM |
| *Juncus roemerianus* (black needlerush) | JUNR |
| *Spartina alterniflora* (medium saltmeadow cordgrass) | SALM |
| *Spartina alterniflora* (tall saltmeadow cordgrass) | SALT |
| *Spartina cynosuroides* (big cordgrass) | SCYN |
| *Spartina patens* (saltmeadow grass) | SPAT |

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### D.3.6.3 Input Coding

After all the necessary input data have been identified on the transect, the Mapping Partner shall divide the transect into continuous segments, each representing a single open fetch or obstruction. Fetches are flooded areas with no obstructions, such as dunes, manmade barriers, buildings, and vegetation. The Mapping Partner shall subdivide fetches at points where the ground elevation abruptly changes and in the transition area of changing SWELs. The Mapping

Partner shall subdivide obstructions at the transect's seaward edge to more accurately model the wave dissipation. Rigid vegetation is to have two to three seaward segments extending 10 to 50 feet, and the first two or three rows of buildings are to have a segment for each row. Marsh vegetation will be subdivided by the WHAFIS model, and thus segmented input is not necessary.

The Mapping Partner shall enter the necessary data using 11 line types, including the Title line. The ten remaining lines each describe a certain type of fetch or obstruction, listed as follows:

- The IE (Initial Elevation) line describes the initial overwater fetch and the initial SWELs.
- The IF (Inland Fetch) and OF (Overwater Fetch) lines define the endpoint stationing and elevation of inland and overwater fetches, respectively.
- Obstructions are categorized either as buildings (BU line), rigid vegetation (VE line), marsh vegetation (VH and MG lines), dunes and other natural or manmade elongated barriers (DU line), or areas where the ground elevation is greater than the 1-percent-annual-chance SWEL (AS line).
- The ET (End of Transect) line enters no data but indicates the end of the input data.

Each line has an alphanumeric field describing the type of input for that line, followed by ten numeric fields describing the parameters.

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To ensure proper modeling, the Mapping Partner shall enter all segments of each transect either as fetches or obstructions, with one input line required for each fetch or obstruction segment. The first two columns of each line identify the type of fetch or obstruction. The remaining 78 columns consist of one field of six columns followed by nine fields of eight columns. The Mapping Partner shall right-justify the numbers in any data field only if no decimal point is used. Decimal points are permitted but not required. The end point of one fetch or obstruction is the beginning of the next. The first two numeric fields of each line are used to read in the stationing (measured in feet from the beginning of transect) and elevation (in feet) of the end point. The last two fields used on each line are for entering new SWELs. An interpolation is performed within a transect segment starting at the closest station with an input SWEL. This interpolation uses the new SWEL input at the end point of the segment and the SWEL input at a previous segment. If these fields are blank or zero, the SWELs remain unchanged.

The input data requirements are summarized below for each line type. The Title line must be the first line, followed by the IE line, followed by any combination of the various fetch and obstruction lines. The ET line must be the last card entered for the transect. A blank line must follow to signify the end of the run. If multiple transects are being run, the Title line for the next transect will follow the blank line. All units are in feet unless otherwise specified.

<u>TITLE Line (Title)</u>

This line is required and must be the first input line.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | Blank |
| 1-10 | 3-80 | Title information centered about column 40 |

IE Line (Initial Elevations)

This line is required and must be the second input line. This line is used to begin a transect at the shoreline and compute the wave height arising through the overwater fetch.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | IE |
| 1 | 3-8 | Stationing of end point of initial overwater fetch in feet (zero at beginning of transect) |
| 2 | 9-16 | Ground elevation at end point in feet (usually Low Water Datum at beginning of transect) |
| 3 | 17-24 | Overwater fetch length (miles), if wave condition is to be calculated. Values of 24 miles or greater yield identical results. |
| 4 | 25-32 | 10-percent-annual-chance SWEL in feet |
| 5 | 33-40 | 1-percent-annual-chance SWEL in feet |
| 6 | 41-48 | Initial wave height; a blank or zero causes a default to a calculated wave height |
| 7 | 49-56 | Initial wave period (seconds); a blank or zero causes a default to a calculated wave period. The period is usually the most convenient wave specification for Great Lakes cases. |
| 8-10 | 57-80 | Not used |

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AS Line (Above Surge)

This line is used to identify the end point of an area with ground elevation greater than the 1-percent-annual-chance SWEL (such as a high dune or land mass). It is used when the ground surface temporarily rises above the 1-percent-annual-chance SWEL. The line immediately preceding the AS line must enter the stationing and elevation of the point at which the ground elevation first equals the 1-percent-annual-chance SWEL. The SWEL on the leeward side may be different from the SWEL on the windward side. The ground elevation entered on the AS line must equal the SWEL that applies to the leeward side of the land mass. The computer calculations will be terminated if a ground elevation greater than the 1-percent-annual-chance SWEL is encountered.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | AS |
| 1 | 3-8 | Stationing at end point in feet of area above 1-percent-annual-chance SWEL |
| 2 | 9-16 | Ground elevation in feet at end point |
| 3 | 17-24 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to the 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

BU Line (Buildings)

This line enters information needed to compute wave dissipation at each group of buildings.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | BU |
| 1 | 3-8 | Stationing of end point in feet of group of buildings |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | Ratio of open space between buildings to total transverse width of developed area |
| 4 | 25-32 | Number of rows of buildings |
| 5 | 33-40 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 6 | 41-48 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 7-10 | 49-80 | Not used |

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DU Line (Dune)

This line enters information necessary to compute wave dissipation at substantial sand dunes and other natural or manmade elongated barriers (e.g., levees, seawalls).

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | DU |
| 1 | 3-8 | Stationing at top of dune or barrier in feet |
| 2 | 9-16 | Elevation at top of dune or barrier in feet |
| 3 | 17-24 | A blank or zero indicates a dune or other natural barrier; any other number indicates a seawall or other manmade barrier |
| 4 | 25-32 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 5 | 33-40 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; |

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| | | otherwise new 1-percent-annual-chance SWEL |
| 6-10 | 41-80 | Not used |

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## IF Line (Inland Fetch)

This line enters the parameters necessary to compute wave regeneration through inland fetches and over shallow inland waterbodies. The IF regeneration is computed using overland wind speed of 30 mph for Great Lakes floods.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | IF |
| 1 | 3-8 | Stationing at end point of fetch in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

## OF Line (Overwater Fetch)

This line enters the parameters necessary to compute wave regeneration over large bodies of water (i.e., large lakes, bays) using overwater wind speed of 40 mph for Great Lakes floods. If an inland waterbody is sheltered and has a depth of ten feet or less, the IF line calling for overland wind speeds should be used.

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| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | OF |
| 1 | 3-8 | Stationing at end point of fetch in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

## VE Line (Vegetation)

This line enters parameters necessary to compute wave dissipation due to rigid vegetation stands.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | VE |
| 1 | 3-8 | Stationing at end point of vegetation in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | Mean effective diameter of equivalent circular cylinder in feet |
| 4 | 25-32 | Average actual height of vegetation in feet |
| 5 | 33-40 | Average horizontal spacing between plants in feet |
| 6 | 41-48 | Drag coefficient; a blank or zero causes a default to 1.0 |
| 7 | 49-56 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 8 | 57-64 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 9-10 | 65-80 | Not used |

## VH Line (Vegetation Header for Marsh Grass)

Marsh grass is often part of a plant community that may consist of several plant types. The VH line is used to enter data that apply to all plant types modeled in the transect segment. To enter data for each plant type, MG lines for each plant type must follow the VH line.

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| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | VH |
| 1 | 3-8 | Stationing at end point of marsh vegetation segment in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | $Reg_p$, number of the primary seacoast region for default plant parameters. Leave blank for Great Lakes computations. |
| 4 | 25-32 | $Wt_p$, weighting factor for the primary seacoast region. Not applicable for Great Lakes analyses. |
| 5 | 33-40 | $Reg_s$, number of secondary seacoast region. Not applicable for Great Lakes analyses. |
| 6 | 41-48 | $N_{p1}$, number of plant types; range is 1 to 10, inclusive. One MG line is required for each plant type. |
| 7 | 49-56 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 8 | 57-64 | A blank or zero indicates no change to the 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 9 | 65-72 | Not used |
| 10 | 73-80 | This field is for overriding the default method of averaging flood hazard factors in A Zones; if 1 in column 80, averaging process begins or ends at end of vegetation segment; otherwise, default averaging method is used |

MG Line (Marsh Grass)

This line is used to enter data for a particular plant type. The first MG line must be preceded by a VH line. For the common seacoast marsh grasses listed in Table D-21, potentially useful default values are supplied in Table D-22. If a plant type not listed in the table is used, then appropriate data must be developed for Fields 2-9.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | MG |
| 1 | 5-8 | Marsh plant type abbreviation (see Table 10) |
| 2 | 9-16 | $C_D$, effective drag Coefficient; default value is 0.1 |
| 3 | 17-24 | $F_{cov}$, decimal fraction of vegetated area to be covered by this plant type; a blank or zero causes a default to be calculated so that each plant type is represented equally |
| 4 | 25-32 | h, mean unflexed height of stem (feet); for marsh plants, the inflorescence is not included |
| 5 | 33-40 | N, number of plants per square foot |
| 6 | 41-48 | $D_1$, base stem diameter (inches) |
| 7 | 49-56 | $D_2$, mid stem diameter (inches) |
| 8 | 57-64 | $D_3$, top stem diameter (inches) |
| 9 | 65-72 | $CA_b$, ratio of the total frontal area of cylindrical part of leaves to frontal area of main stem |
| 10 | 73-80 | Not used |

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ET Line (End of Transect)

This line is required and must be the last input card because it identifies the end of input for the transect.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | ET |
| 3-10 | 3-80 | Not used |

**Table D-12. Significant Marsh Plant Types in Each Seacoast Region and WHAFIS Default Regional Plant Parameter Data**

| REGION NO. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| REGION NAME: | NORTH ATLANTIC | MID-ATLANTIC | SOUTH ATLANTIC | SOUTH FLORIDA | NORTHEASTERN GULF | DELTA PLAIN | CHENIER PLAIN | SOUTH TEXAS |
| CLAD | --- | --- | --- | 7.50(+)<br>0.0656<br>6 | 6.00(2)<br>0.0260<br>6 | --- | --- | --- |
| DIST | --- | 0.78(1)<br>0.0039<br>211 | 1.00(1)<br>0.038<br>243 | 1.00(+)<br>0.0038<br>248 | ---<br>--- | 1.08(4)<br>0.0035<br>102 | 1.08(+)<br>0.0035<br>102 | --- |
| JUNM | 1.23(1)<br>0.0042<br>300 | 1.23(+)<br>0.0042<br>300 | --- | --- | --- | --- | --- | --- |
| JUNR | --- | 2.95(+)<br>0.0095<br>147 | 2 95(+)<br>0.0095<br>147 | --- | 2.95(3)<br>0.0095<br>147 | 3.00(4)<br>0.0106<br>83 | 2.95(+)<br>0.0095<br>147 | --- |
| SALM | 1.39(1)<br>0.0184<br>45 | 1.06(1)<br>0.0103<br>36 | 1.63(1)<br>0.0141<br>12 | 1.63(+)<br>0.0141<br>12 | --- | 1.67(4)<br>0.0141<br>21 | 2.62(5)<br>0.0211<br>16 | --- |
| SALT | 1.86(1)<br>0.0175<br>37 | 2.21(1)<br>0.0169<br>18 | 3.20(1)<br>0.0183<br>10 | 3.20(+)<br>0.0183<br>10 | --- | 3.20(4)<br>0.0183<br>10 | 3.20(+)<br>0.0183<br>10 | --- |
| SCYN | --- | --- | 8 29(+)<br>0.0492<br>6 | --- | --- | 4.00(4)<br>0.0267<br>7 | --- | --- |
| SPAT | 1.03(1)<br>0.0025<br>409 | 0.85(1)<br>0.0019<br>327 | 1.65(1)<br>0.0019<br>236 | --- | 2.58(2)<br>0.0026<br>236 | 1.88(4)<br>0.0016<br>333 | 1.88(+)<br>0.0019<br>333 | --- |

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Data arranged in vertical triplets:

h, stem height below inflorescence, in feet
D, base diameter, in feet
N, number density, in inverse square feet

Parenthetical references indicate data source:

1 = Hardisky and Reimold, 1977
2 = Monte, August 1983
3 = Kruczynski, Subrahmanyam, Drake, 1978
4 = Hopkinson, Gosselink, Parrondo, 1980, Diameters extrapolated
5 = Turner and Gosselink, 1975, Diameters extrapolated
+ = Extrapolated Data
--- = Insignificant amounts of this plant type in the region

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### D.3.6.4 Error Messages

While using the WHAFIS program, the Mapping Partner may encounter the error messages listed below.

- "AS card ground elevation less than SWEL, should use other type card, job dumped."

  Only use AS (above surge) line when the ground elevation is above the SWEL. Can otherwise use IF, OF, BU, DU, VE, or VH.

- "Ground elevation greater than surge elevation encountered, job dumped."

  If ground elevation is above surge elevation, AS card should be used.

- "Average depth less than or equal to zero, job dumped."

  The water depth must be greater than zero or a wave height cannot be computed. Check the SWEL and the ground elevation if point of job dump is not the last point along the transect profile.

- "The above card contains illegal data in the first 2 columns."

  Check input data for incorrect values or input within wrong columns. Aside from the title line, the first two columns in each line should contain the card identifiers.

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- "Transmitted wave height at last fetch or obstruction = _____ which exceeds 0.5."

  Code the transect profile up to the inland limit where ground elevation intersects the SWEL so that wave height should decrease to zero. If the scope of work ends at the corporate limits before the ground elevation meets the SWEL, this message can be ignored.

- "Array dimensions exceeded. Job dumped."

  Size of the array is limited and the number of input parameters has exceeded the array. Check the number of input parameters at the location where the job dumped.

- "Invalid data in field 1 of IF card," etc.

  Check input data to make sure that data are in correct columns.

- "Wave period less than or equal to zero in subroutine fetch. Abort run."

  Either a fetch length or a wave period must be input for the program to run properly. Check input data.

- "Invalid data in field 3 or field 5 of VH card."
  Check input data.
- "Invalid data in field 4 of VH card."

  Check input data.

- "Invalid data in field 3 of MG card."

Check input data. The fraction of vegetated area covered by the stated plant type should be a decimal number between 0.0 and 1.0.

- "Missing MG card or incorrect data in field 6 of VH card."

  A MG card must always follow the VH card. Field 6 of the VH card pertains to the number of plant types, and one MG card is required for each plant type.

- "Invalid input data."

  Check input data for invalid characters, such as an O instead of a zero. Check to be sure that all data are in their correct columns.

- "Fcov was found to be negative for plant type = _____."

  Check input data to be sure that the decimal fraction of the vegetated area covered by the plant type is not negative.

- "Ncov is .LE. zero in Sub.Lookup when it should be .GT. zero. Abort run."

  Check input for number of plants covering the area.

- "The first card is not an IE card, this transect is aborted. Continued to next transect."

  The first card after the title line must always be an IE card. Check input data.

- "**** The surge elevation at this station (stationing ____), which is ____ card, is less than the ground elevation. The interpolation process is continued. *** Please double check the surge and ground elevations in the vicinity of this station!!!!!!"

  The surge elevation should not be below the ground elevation. If the interpolated surge elevation is interpolated below the ground elevation, insert additional cards to specify surge and ground elevations and use an AS card if necessary.

- "Interpolation line cuts off more than two portions of high ground ridge. This transect is aborted, re-assign 1-percent-annual-chance elevations at high ground stations."

  When the interpolated value falls below the ground elevation, insert additional cards to better model the area and set the SWEL equal to the ground elevation where appropriate. Insert AS cards as necessary.

- "**** Unreasonable high ground elevation at station ____ which is ____ card. This transect is aborted, continued to next transect. **** Double check the surge and ground elevations in the vicinity of this station. If the ground elevations are correct, either assign a higher surge elevation or use AS cards."

  Add additional input data as necessary to better define the ground elevation and surge elevation in this area.

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### D.3.6.5 Output Description

The output of the program provides all the data necessary for plotting the BFEs and flood insurance risk zones along the transect. The output is in six parts:

**Part 1 - Input**

This is a printout showing all input data lines and the parameters assigned to each line, both manually and by default. This is followed by a more detailed printout with column headings for each input data line. When VH and MG Lines are used, a separate insert will be printed directly beneath the MG Line showing any default values supplied by the computer.

**Part 2 - Controlling Wave Heights, Spectral Peak Wave Period, and Wave Crest Elevations**

This is a list of the calculated controlling wave heights, spectral wave peak periods, and wave crest elevations at the end point of each fetch and obstruction of the input, and at calculation points generated between the input stations.

**Part 3 - Location of Areas Above 1-Percent-Annual-Chance Surge**

This is a list of the locations of areas where the ground elevation is greater than the 1-percent-annual-chance stillwater (surge) elevation. Only areas identified by AS lines are listed.

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**Part 4 - Location of Surge Elevations**

This is a list of the 10- and 1-percent-annual-chance stillwater (surge) elevations and the stationing of the points where each set of SWELs first becomes fully effective.

**Part 5 - Location of V Zones**

This is a list of the locations of the V/A Zone boundary and locations of the V Zone areas relative to these boundaries. The stationing is given for each V/A Zone boundary. The locations of the V Zone areas in relation to these boundaries are given as windward or leeward of the boundary.

**Part 6 - Numbered A Zones and V Zones**

This is a list of the zone data needed to delineate the flood hazard boundaries on the FIRM. The location of a flood zone boundary and the wave crest elevation at that boundary are given on the left. Between the boundary listings are the zone designations and FHFs. Under FEMA's Map Initiatives Procedure guidelines, all numbered V and A Zones should be changed to VE and AE Zones, respectively (elevations will not change), and the FHFs can be ignored (FEMA, 1991). When the same zone and elevation are repeated in the list, they should be treated as a single zone.

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## D.3.7 Mapping of Flood Elevations and Zones

This subsection discusses procedures for reviewing the initial model results and identifying flood insurance risk zones, and provides guidance for depicting the analysis on the FIRM.

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### D.3.7.1 Review and Evaluation of Basic Results

The results of the technical analyses performed for the FIS or map revision determine the special flood hazards shown on the FIRM. The coastal hazards mapped on the FIRM depict the effects of erosion on overland wave propagation, the impact of steep beach slopes and bluffs on wave runup elevation, and the areas subject to high velocity wave hazards (V Zones). Because the FIRM is used for floodplain management and flood insurance determination, the Mapping Partner shall ensure the SFHAs are mapped with as much accuracy as possible.

With the results of the various analyses at hand, the Mapping Partner shall place flood elevations and zones on the work map or up-to-date topographic survey map, after first reviewed them for their consistency with the terrain and conditions they represent and with historical data. In using the models, it is possible to forget that the transects represent real shorelines of sandy beaches, rocky or cohesive bluffs, wetlands, etc., being subjected to extremely high water, waves, and winds. The Mapping Partner shall review the results of the analyses to determine if they are a reasonable representation of the coastal areas being modeled.

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Although historical data from a storm closely approximating the base (1-percent-annual-chance) flood are seldom available, flood data for less intense storms will still indicate, at a minimum, what areas should be in flood zones. For instance, if a storm produced an extreme flood that caused structural damage to houses 100 feet from the shoreline, yet the flood was below the 1-percent-annual-chance flood SWEL, a reasonable Zone VE width would be at least 100 feet. Similarly, houses more than 100 feet from the shoreline that are flooded but not structurally damaged by the same storm must be at least in a Zone AE, AH, or AO. If the analyses of the 1-percent-annual-chance flood produce flood zones and elevations indicating lesser hazards than those recorded for a more common storm, the Mapping Partner shall reevaluate the analyses. There may be an explanation for the inconsistency (other than an error in the input data); for instance, a new coastal structure may act to reduce flood hazards locally or a big storm may have significantly altered the terrain. A field check should be undertaken to determine whether such an explanation exists.

If no explanation for the inconsistency is apparent, the Mapping Partner shall examine the data input to the models including checking that the SWELs, wave heights, wave periods, and fetch lengths were input correctly and are consistent with the historical data. A further field check could examine whether buildings or structures modeled would be destroyed by the storm or whether the buildings are on pilings above the flooding.

The Mapping Partner also shall evaluate the results of the erosion assessment by comparing the eroded profile to past effects, whether in the form of profiles, photographs, or simply

descriptions. A general idea of what happened previously can be sufficient. Judgment and experience must be used to project previous storm effects to the 1-percent-annual-chance flood conditions and to ensure that the eroded profile is consistent with previous events.

The main point emphasized here is that the results are not to be blindly accepted. Many uncertainties and variables in coastal processes may occur during an extreme flood, and many possible adjustments to methodologies for treating such an event may be appropriate. The validity of any model is demonstrated by its success in reproducing recorded events. Therefore, the model results must be in basic agreement with past flooding patterns and results, and historical data must be used to evaluate these results.

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### D.3.7.2 Identification of Flood Insurance Risk Zones

Interpretation and accurate delineations of the hazards on the maps are the final critical elements in a coastal flood hazard study. The transect used in the wave elevation determination and the resulting wave analyses, whether for wave height or wave runup, is the tool by which the results can be mapped. Mapping Partner shall identify the flood zones and BFEs should be identified on each of the transect plots before transferring the information and delineating the hazard zones and BFEs on the work maps. It should be noted that because of changes in the NFIP in 1988 that redefined the Coastal High Hazard Area and incorporated wave runup hazards, Part 6 of the WHAFIS output, discussed in Section D.3.6, is no longer used to plot zones on the work maps.

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It is important to understand the interrelationship of the three key elements in determining the flood hazard zone and BFE. These elements are the existing transect ground profile, the eroded transect ground profile, and the wave envelope. The existing transect ground profile may be modified by the presence of erosion forces along the shoreline, if appropriate, in which case the flood hazard zone depicted by the transect and wave analyses results may not appear to reflect the topography shown for existing conditions with ground elevations higher than the BFE. The eroded transect ground profile, developed using treatment described in Subsection D.3.4, must be used in the wave analyses described in Subsections D.3.5 and D.3.6. The BFEs and the topography shown on the work maps may differ from those produced by the erosion treatments for a shoreline reach and the wave analyses. This is because the topography of the work maps does not reflect the erosion of the shoreline determined as part of the coastal FIS or map revision request. To clarify areas where these discrepancies exist, the Mapping Partner shall provide a description of the areas subject to erosion treatments either in the coastal FIS Report or in the supporting engineering report for a map revision request.

The wave envelope is the most important of the three elements for identifying the flood hazard zone. The wave envelope is a combination of representative wave runup elevation and the wave crest profile determined by the wave results computed using the WHAFIS program. The wave crest profile is plotted on the final transect ground profile (with or without the effects of erosion) based on the results computed and shown in Part 2 of the WHAFIS output. For wave runup elevation results, a horizontal line is extended seaward from the computed runup elevation to its intersection with the wave crest profile. This determines the wave envelope profile for the

results combined from the WHAFIS wave height analysis and the RUNUP 2.0 wave runup analysis, as shown in Figure D-46. If the runup elevation is greater than the maximum wave crest elevation, the wave envelope will be a horizontal line at the runup elevation. Conversely, if the wave runup is negligible or was not modeled because of coastal processes and shoreline conditions that prevent significant runup from occurring, the wave crest profile alone will become the wave envelope.

Before transferring the established wave envelope information from each transect onto the work maps, it is important to understand the NFIP coastal flood zones and how to determine their location along the transect plot. The descriptions are as follows:

Zone VE - Coastal High Hazard Areas where wave action and/or high velocity water can cause structural damage in the base (1-percent-annual-chance) flood. The three criteria for determining a Zone VE area are: (1) the area where 3 foot or greater wave height could occur (this is the area where the WHAFIS wave crest profile is 2.1 feet or more above the SWEL), (2) the area where the eroded ground profile is 3 feet or more below the representative runup elevation, and (3) the primary frontal dune, by definition. Subdivided into elevation zones with BFEs assigned.

Zone AE - Areas of inundation by the base (1-percent-annual-chance) flood, including wave heights less than 3 feet and runup elevations less than 3 feet above the ground. Also subdivided into elevation zones with BFEs assigned.

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Zone AH - Areas of shallow flooding or ponding, with water depth equal to 3 feet or less. Usually not subdivided, but a BFE is assigned.

Zone AO - Areas of "sheet-flow" shallow flooding where overtopping water flows into another flooding source. Assigned with 1-, 2-, or 3-foot depth of flooding.

Zone X - Areas above base (1-percent-annual-chance) flood inundation. On the FIRM, shaded Zone X is inundated by the 0.2-percent annual chance flood, unshaded Zone X is above 0.2-percent annual chance flood.

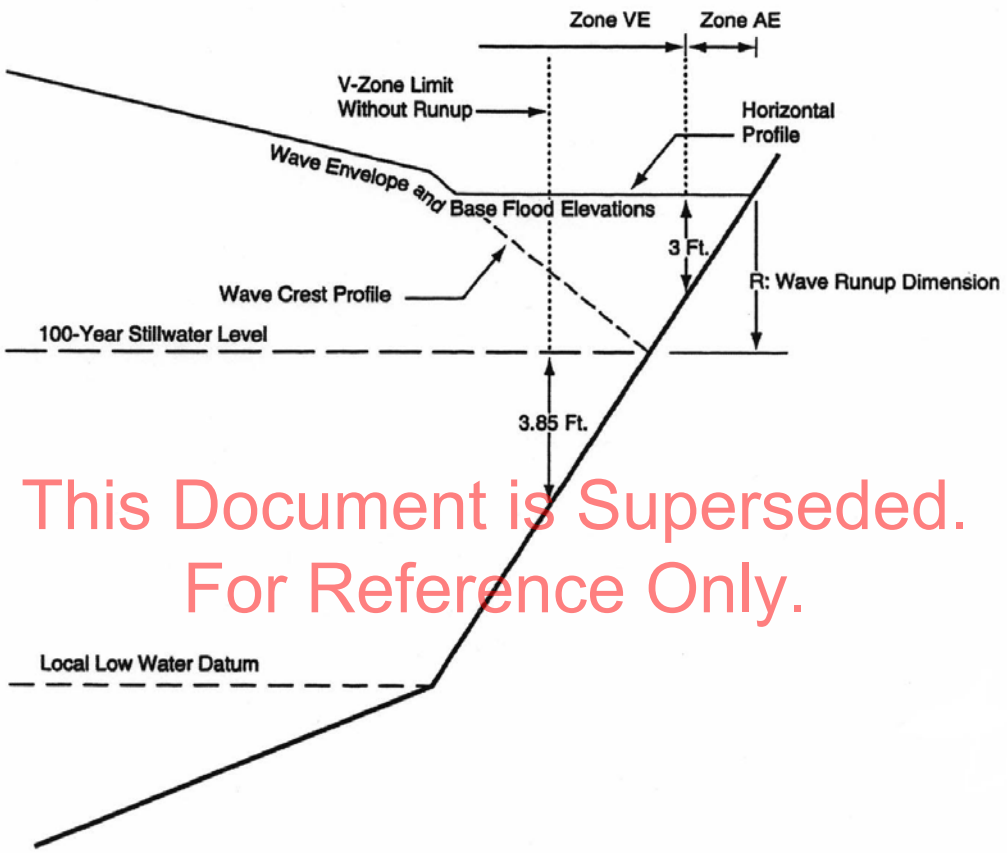


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**Figure D-46. Wave Envelope Resulting from Combination of Nearshore Crest Elevations and Shore Runup Elevation.**

The first step in identifying the flood insurance risk zones on the transect is locating the inland extent of the VE Zone, also known as the VE/AE boundary. Once the Mapping Partner has identified the VE Zone limits for each of the three criteria described above, the Mapping Partner shall place the VE/AE boundary at the location that is furthest landward. The AE Zone will extend from the VE Zone limit to the inland limit of the 1-percent-annual-chance flood inundation, which is a ground elevation equal to the representative runup elevation, or the 1-percent-annual-chance SWEL if runup is negligible or not included in the wave analyses. Additional areas of shallow flooding or ponding for the 1-percent-annual-chance flood event can be designated as Zone AH or Zone AO. All areas above the 1-percent-annual-chance flood inundation are Zone X.

The Mapping Partner shall then subdivide the AE and VE Zones into elevation zones with whole-foot BFEs assigned. Ideally, to help in floodplain management and insurance determinations for buildings and property, the Mapping Partner shall establish an elevation zone for every BFE in the wave envelope. However, the FIRM scale may limit the number of zones that can be mapped. For the FIRM to be legible, there must be a minimum width for the zones. For coastal areas, the minimum zone width is 0.2 inch. For identifying elevation zones on the transect, the minimum width is 0.2 times the final FIRM scale; for example, 80 feet for a FIRM at a scale of 1 inch equals 400 feet, 100 feet for a FIRM at a scale of 1 inch equals 500 feet.

The Mapping Partner shall not subdivide the horizontal runup portion of the wave envelope, if any; the runup elevation, rounded to the nearest whole foot, is the BFE. However, the Mapping Partner shall subdivide the WHAFIS wave crest profile. Generally, the VE Zone is subdivided first. Initially, the Mapping Partner shall mark the location of all the elevation zone boundaries on the transect. Because whole-foot BFEs are being used, these must always be at the location of the half-foot elevation on the envelope.

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The Mapping Partner shall combine elevation zones that do not meet the minimum width criterion with an adjacent zone or zones to yield an elevation zone that is wider than the minimum. The BFE for this combined zone is a weighted average of the combined zones. Often in subdividing VE Zones, the maximum BFE is located just inside the mapped shoreline, and the remainder of the VE Zone is then subdivided into minimum width elevation zones.

The Mapping Partner shall subdivide the AE Zone, if it is wide enough, in the same manner. If the total AE Zone is less than the minimum width, the lowest elevation VE Zone is usually assigned to that area. This situation typically occurs for steep or rapidly rising ground profiles, and it is not unreasonable to designate the entire inundated area as a VE Zone.

Relatively low areas inland of the AE Zone may be subject to shallow flooding or ponding of flood water and designated as AH or AO Zone. Such designations can be relatively common landward of coastal structures and dunes, where wave overtopping occurs.

Identifying appropriate zones and elevations may require particular care for dunes, given that the entire primary frontal dune is defined as Coastal High Hazard Area. Although the analyses may have determined a dune will not completely erode and wave action should stop at the retreated

duneface with only overtopping possibly propagating inland, the entire dune is still designated as a VE Zone. The BFE at the duneface is assigned for the remainder of the dune.

It may seem unusual to use a BFE that is lower than the ground elevation, although this is actually fairly common. Most of the BFEs for areas where the dune was assumed to be eroded are also below existing ground elevations. In these cases, it is the VE Zone designation that is most important to the NFIP; current regulations require structures to be built on pilings and prohibit alterations to the dune.

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### D.3.7.3 Mapping Procedures

The final work maps prepared from the results of the coastal FIS or map revision request will be used to produce a new or revised FIRM for the affected community. The work map is essentially the base map selected for the study area, as described in Subsection D.3.2, and the depiction and delineation of the coastal flood hazards that reflect the results of the wave elevation determinations and flood zones established for each respective area. The Mapping Partner shall seta the work map up with contour lines, buildings, structures, vegetation, and transects used in the wave analyses clearly and accurately located.

The Mapping Partner shall transfer the flood zones and wave elevations identified on the transects to the work maps and interpolate the boundaries between the transects. The interpolation of the results at the transects and between the transects for the results of the wave height and wave runup analyses involves judgment and skill in reading the topographic and land cover information shown on the work maps. The time and effort put forth to determine the wave elevations will be negated if the results cannot be properly delineated on the work maps and shown on the FIRM. Because roads are the only fixed physical features shown on the FIRM, it is very important that other features and the flood zone boundaries are properly located on the work maps in relation to the centerline of the roads as they will appear on the FIRM. Other important considerations for mapping the results of the coastal FIS or map revision request discussed below include shoreline fluctuations, flood zone widths, interpolation of the transitions between zones for the represented transects, and the depiction and delineation of the Zone X shaded special flood hazard areas in areas subject to wave runup hazard.

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An important but potentially ambiguous map feature is the depicted shoreline in the study area. Great Lakes shorelines are subject to large position changes, given shore erosion or accretion along with the considerable range in mean lake levels. The shoreline location may vary among the transects analyzed because of historical erosion or accretion not shown or accounted for on existing maps, but some clearly designated shoreline should be used for the work maps. For Great Lakes studies, the Mapping Partner shall ensure the depicted shoreline corresponds to the land intercept of Low Water Datum, as given in Table D-12 and usually shown on USGS maps. (It is customary to delineate flood zones only landward of the shoreline.)

The Mapping Partner shall transfer the identified elevation zones for each transect to the work maps, locating the boundaries along the transect line so that boundary lines can be interpolated

between transects, assuring that the boundaries are marked at the correct location. Because of the erosion assumptions, the location of the elevation 0.0 NGVD shoreline changes on the transect but not the work maps. The transect profile is used to determine the location of the zone change in relation to a physical feature, such as a ground contour, road, the back side of a row of houses, 50 feet into a vegetated area, etc. The boundary line along this feature for the area represented by that transect is then delineated.

The Mapping Partner shall check the widths of the zones being delineated carefully; if they narrow to less than 0.2 inch, they should be tapered to an end. Likewise, if an averaged elevation zone becomes much wider, it may be possible to break it into two elevation zones, both wider than 0.2 inch. Consideration of the final map scale of the FIRM to be produced from the work maps will help in determining how the zones should be combined and averaged.

One of the more difficult steps in delineating coastal flood zones and elevations is the interpolation and transition between transect results. Good judgment and an understanding of typical flooding patterns are the best tools for this job. The first step is to locate on the work maps any area of transition that is not exactly represented by either transect. The next step is to delineate the flood boundaries for each transect up to this area. Then consideration should be given to how a transition can be made across this area to connect matching zones, and still have the boundaries follow logical physical features. If there are other transects that are similar to this area, they could give an indication of flooding. Sometimes the elevation zones for the two contiguous transects are not the same; thus, some zones may have to be tapered to an end, or enlarged and divided in the transition area.

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Communities with significant flooding hazards from wave runup may have one transect representing more than one area because the areas have similar shore slopes. In this case, the different areas are identified, and the results of the typical transect delineated in each area. Transition zones may be necessary between areas with high runup elevations to avoid large differences in BFEs and to smooth the change in flood boundaries. These zones, which should be fairly short, should cover the shore segment with a slope not exactly typical of either area. The transition elevation is determined by examining runup transects with similar slopes and using good judgment. Transition zones should not be used if there is a very abrupt change in topography, such as is found at the end of a structure.

Lastly, Mapping Partner shall map the Zone X (shaded) areas. Areas below the 0.2-percent annual chance SWEL and not covered by any other flood zone are designated Zone X shaded and shown on the FIRM. Often the maximum runup elevation is higher than the 0.2-percent annual chance elevation; thus, there will be no shaded Zone X in that area. The Mapping Partner shall designate all other areas as Zone X without any shading.

These *Guidelines* were compiled to give guidance in the preparation of coastal FISs and map revision requests. The collection of accurate and representative data, the correct application of the models, the evaluation and comparison of the results to historical data, and the proper delineation of flood elevations and zones will produce a FIRM that is both technically correct and directly usable for the intended purposes.

During all steps of the study, especially the mapping, the final product and its purposes should be remembered: the FIRM is used to determine flood insurance premiums and regulate building standards.

Because flood elevations are rounded to the nearest whole foot, there is no reason for spending hours to resolve a minor elevation difference. Also, because structures or proposed structures must be located on the FIRM, an attempt should be made whenever possible to smooth the boundary lines and to follow a fixed feature such as a road. In preparing the FIS, not only must the mapped results be technically correct, but the FIRM must be easy for the local insurance agent, building inspector, or permit officer to use.

Additional criteria and submittal requirements are documented in the Certification forms for Study Contractors (SC-1) and Application/Certification form 5 (MT-2) for map revision requests.

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## D.3.8 Required Documentation

The Mapping Partner shall fully document the coastal flood hazard determination for each affected community. Because FIS Reports and FIRMs form the basis of Federal, State, and local regulatory and statutory enforcement mechanisms and are subject to administrative appeal and litigation, Mapping Partners shall ensure that all technical processes and decisions are recorded and documented. The FIS Report may not contain all the documentation that would be needed for a response in the event that the study results are questioned. Therefore, the Mapping Partner shall prepare an engineering report for each study. This report will provide detailed data needed by FEMA or the community to reconstruct or defend on technical grounds the study results. The minimum information required for the engineering report are summarized below.

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**Basic Data**.

In this section, the Mapping Partner shall include all contacts made to obtain data for the study. All basic data used must be fully referenced and, if possible, reproduced in the report. All historical flood information must be documented in this section, even if the Mapping Partner did not use the information in quantitative analyses.

**Transects**

Each transect must be plotted separately and show the erosion assessment, input data for wave models, wave envelope, and zone determination.

**Model Input and Output**

The Mapping Partner shall provide computer printout listings for input and output data for both the Wave Runup and Wave Height Models for all the transects. These listings must be keyed to the transect location map and transect plots.

**Study File**

During the course of the study, the Mapping Partner shall maintain a file containing records of all coordination, activities, and decisions. This is especially important where nonstandard approaches were used and engineering judgment played a significant role. The Mapping Partner shall ensure this file meets the requirements for a Technical Support Data Notebook as documented in Appendix M of these Guidelines.

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## D.3.9 Open Coast Flood Elevations and Wave Information

As discussed in Subsection D.3.2, the draft of "Basic Analyses of Wave Action and Erosion with Extreme Floods on Great Lakes Shores" (Dewberry & Davis, 1995) concluded from historical evidence that extreme floods were usually accompanied by the local 1/2-year wave condition on Lake Ontario, or by the 3-year wave condition on Lakes Erie, Huron, Michigan, and Superior. Examples of appropriate wave conditions derived for numerous sites on each of the Great Lakes are presented in Figures D-47 through D-56 and in Tables D-23 through D-27.

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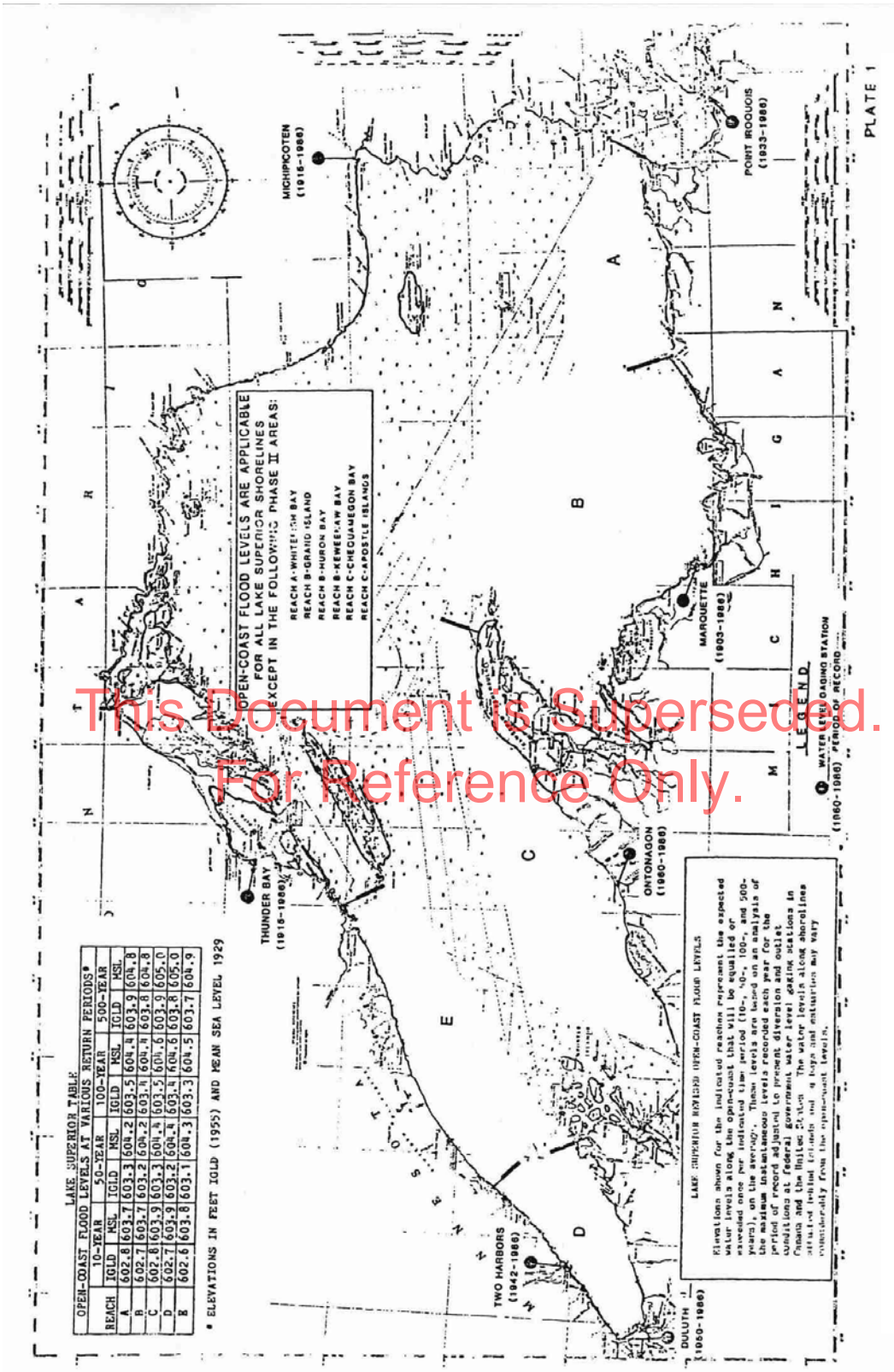


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**Figure D-47. Lake Superior Table and Map of Open Coast Flood Levels (USACE, 1988).**

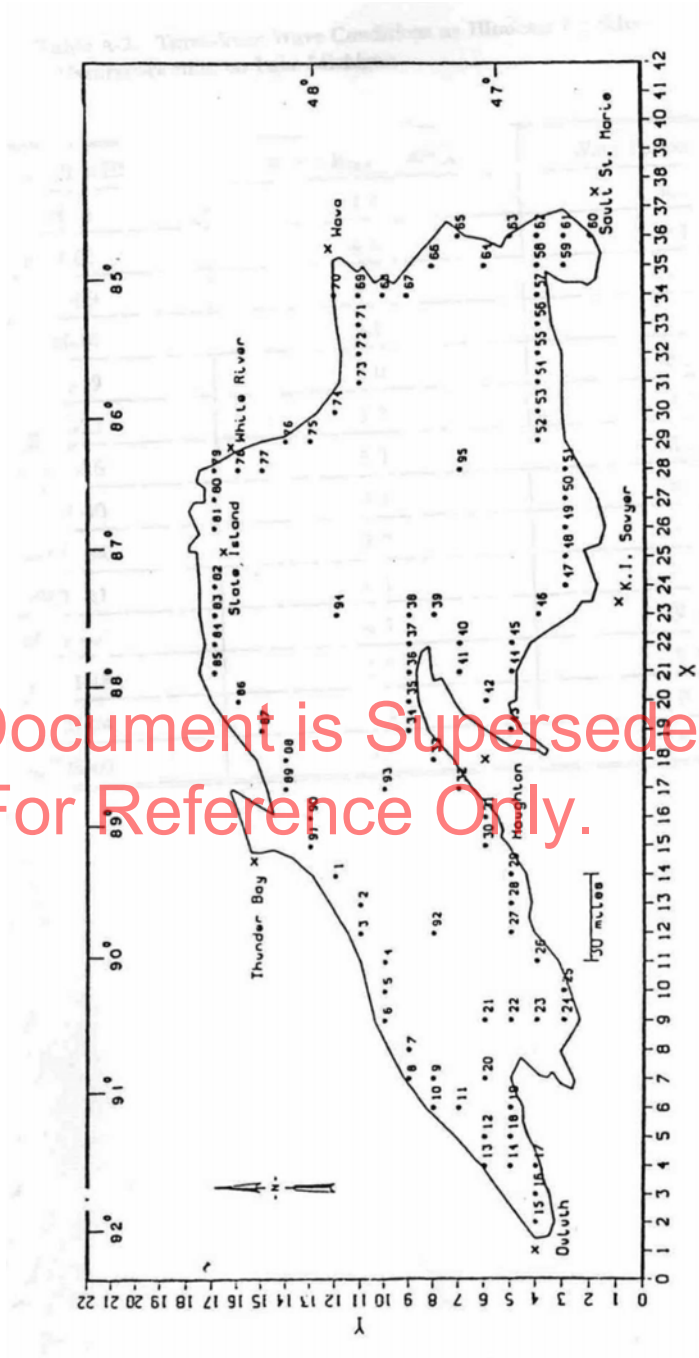


**Figure D-48. Station Location Map for Lake Superior Wave Information Stations.**

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**Table D-23. Three-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Superior**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| SUPER-05 | 6.0 | 10.0 |
| SUPER-13 | 5.8 | 10.0 |
| SUPER-15 | 3.7 | 7.1 |
| SUPER-23 | 4.3 | -- |
| SUPER-29 | 5.0 | 9.1 |
| SUPER-35 | 5.9 | -- |
| SUPER-42 | 5.2 | -- |
| SUPER-47 | 7.7 | 11.1 |
| SUPER-54 | 6.2 | -- |
| SUPER-60 | 4.5 | 7.7 |

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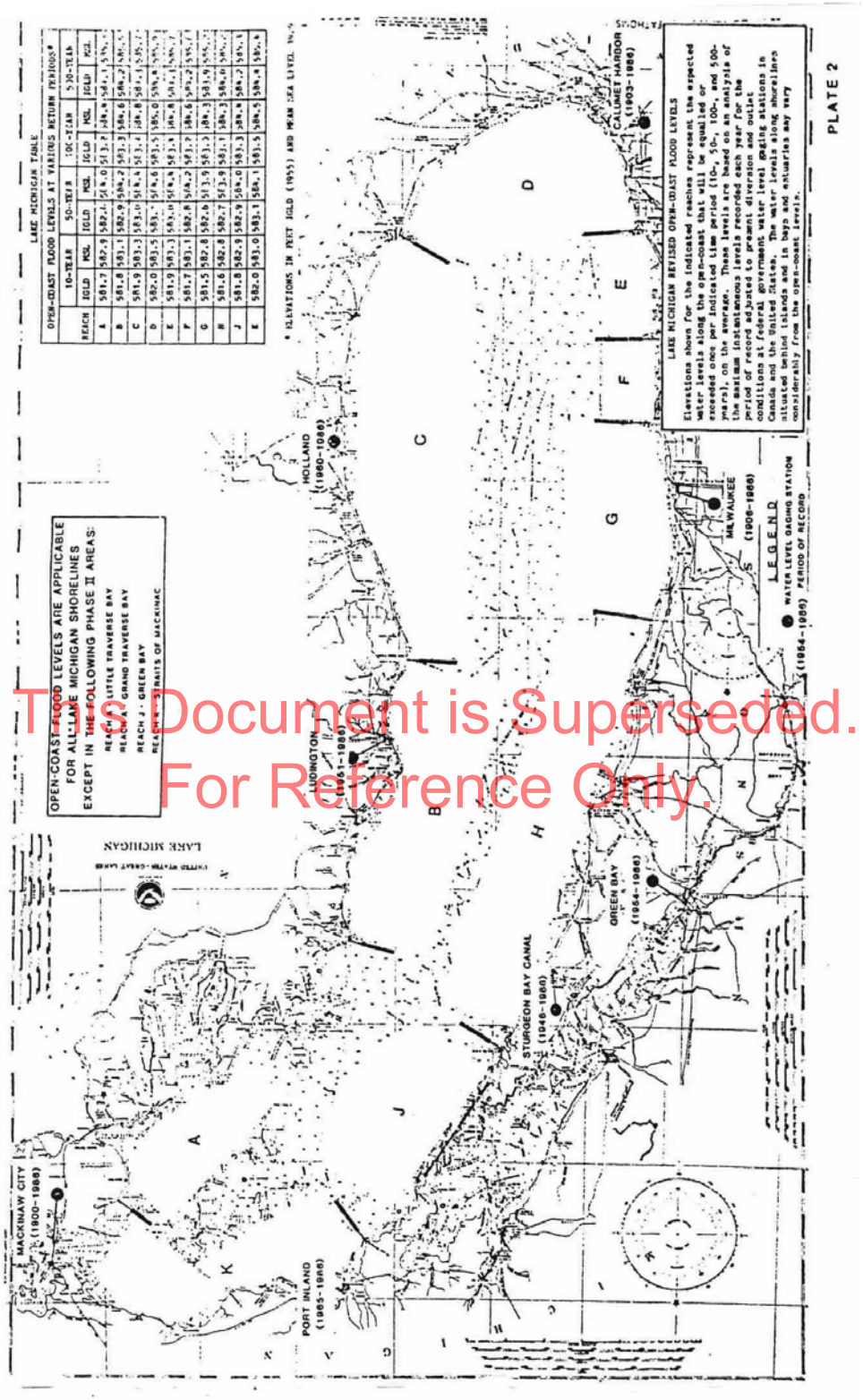


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**Figure D-49. Lake Michigan Table and Map of Open Coast Flood Levels (USACE, April 1988).**

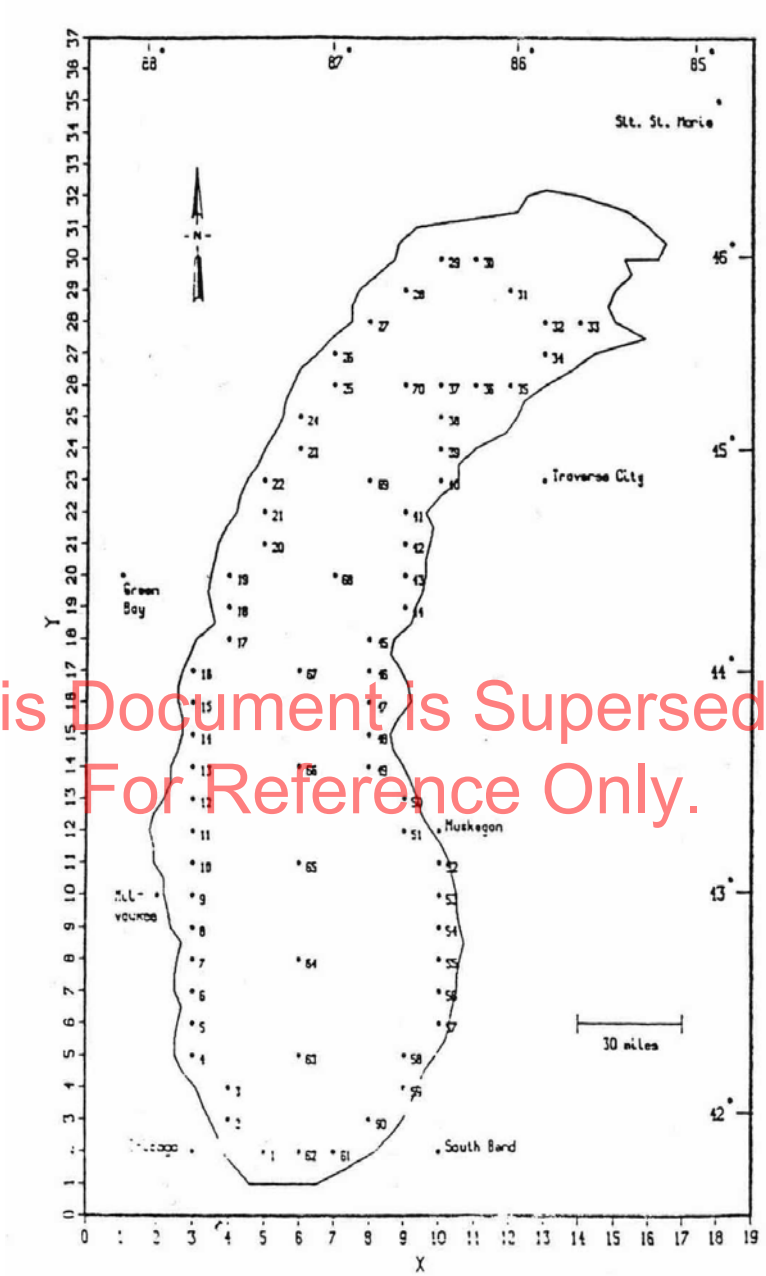


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**Figure D-50. Station Location Map for Lake Michigan Wave Information Stations.**

**Table D-24. Three-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Michigan**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| MICH-01 | 4.4 | 9.1 |
| MICH-03 | 4.6 | 9.1 |
| MICH-09 | 4.7 | 8.3 |
| MICH-14 | 3.9 | -- |
| MICH-19 | 4.0 | 8.3 |
| MICH-22 | 3.7 | 7.7 |
| MICH-26 | 3.3 | 8.3 |
| MICH-30 | 3.4 | 8.0 |
| MICH-34 | 3.7 | -- |
| MICH-41 | 4.1 | -- |
| MICH-46 | 4.7 | 9.1 |
| MICH-48 | 5.2 | 9.1 |
| MICH-54 | 5.2 | 9.1 |
| MICH-60 | 4.5 | 8.3 |

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**Figure D-51. Lake Huron Table and Map of Open Coast Flood Levels (USACE, 1988).**

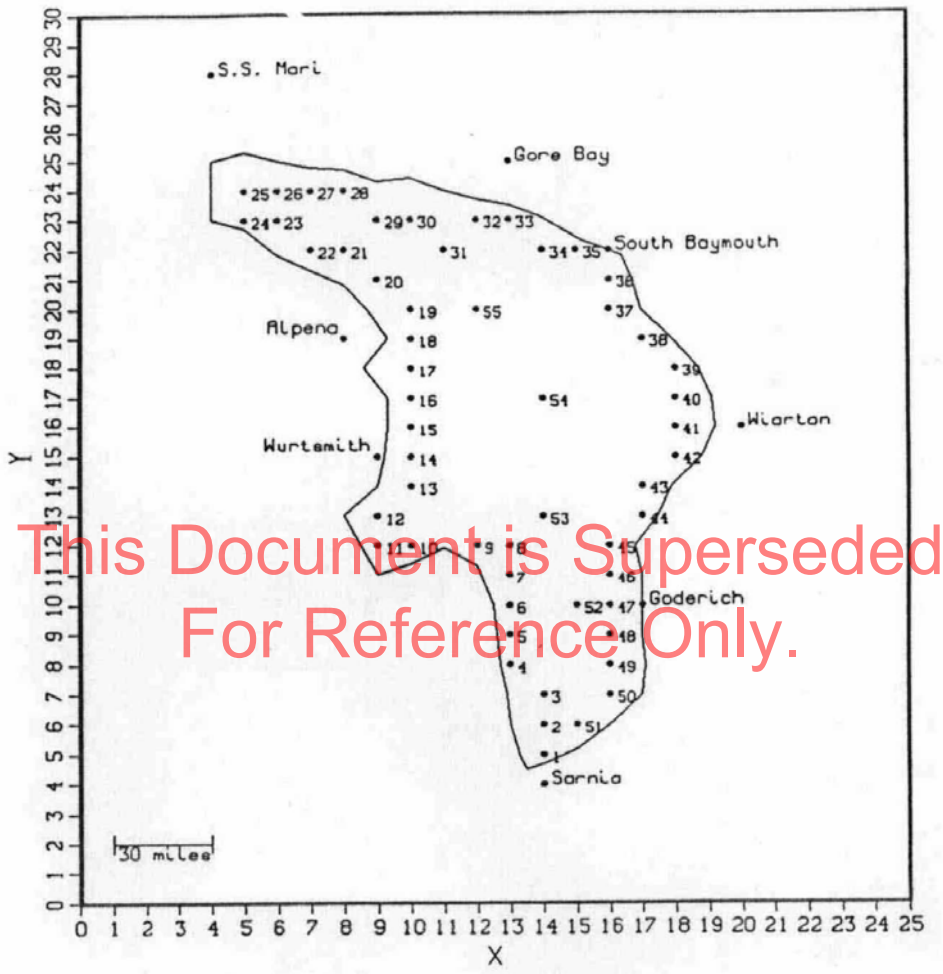


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**Figure D-52. Station Location Map for Lake Huron Wave Information Stations.**

**Table D-25. Three-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Huron**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| HURON-01 | 6.1 | 9.1 |
| HURON-02 | 6.2 | 10.0 |
| HURON-07 | 5.6 | 9.1 |
| HURON-11 | 6.3 | 9.1 |
| HURON-12 | 6.2 | 9.5 |
| HURON-15 | 6.1 | 9.1 |
| HURON-20 | 5.0 | -- |
| HURON-25 | 4.1 | 7.7 |
| HURON-26 | 4.3 | 9.1 |

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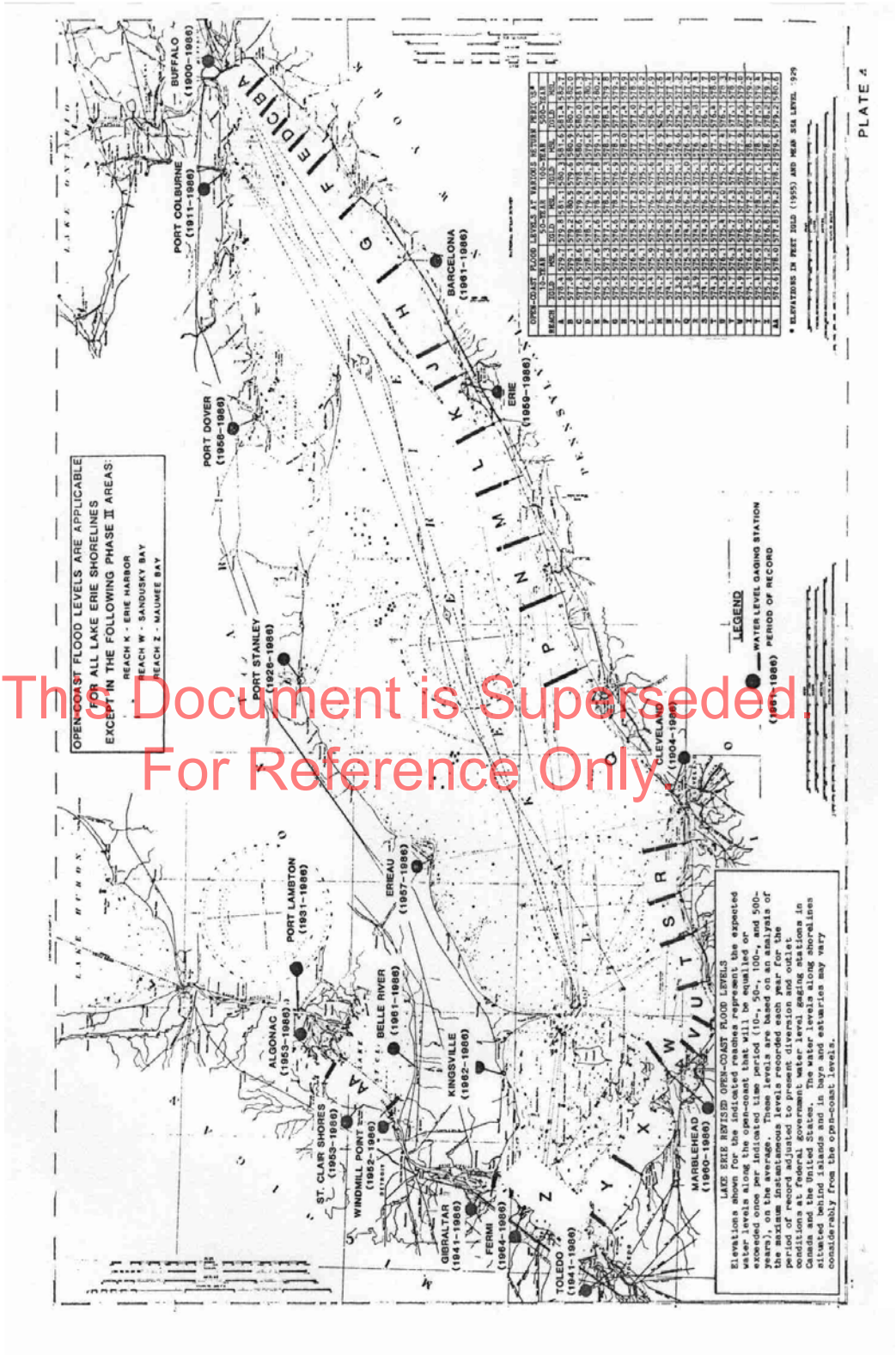


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**Figure D-53. Lake Erie Table and Map of Open Coast Flood Levels (USACE, 1988).**

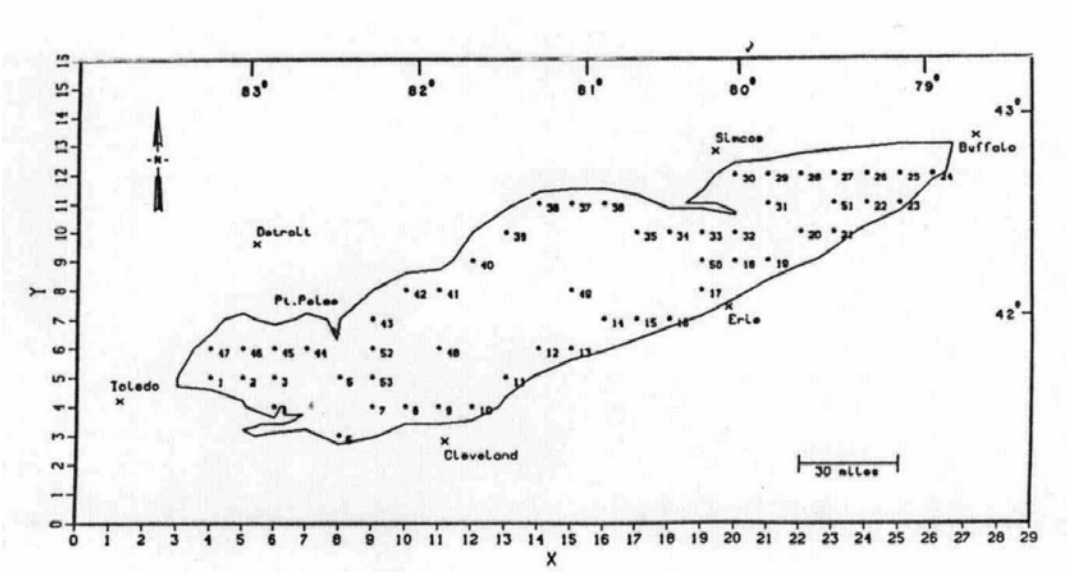


**Figure D-54. Station Location Map for Lake Erie Wave Information Stations.**

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**Table D-26. Three-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Erie**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| ERIE-01 | 2.0 | 6.2 |
| ERIE-04 | 1.9 | 6.2 |
| ERIE-07 | 3.3 | -- |
| ERIE-10 | 3.6 | 7.7 |
| ERIE-12 | 4.0 | 8.3 |
| ERIE-15 | 4.2 | -- |
| ERIE-18 | 4.6 | 9.1 |
| ERIE-21 | 4.9 | 9.1 |
| ERIE-24 | 4.2 | 9.1 |
| ERIE-47 | 1.8 | 5.6 |

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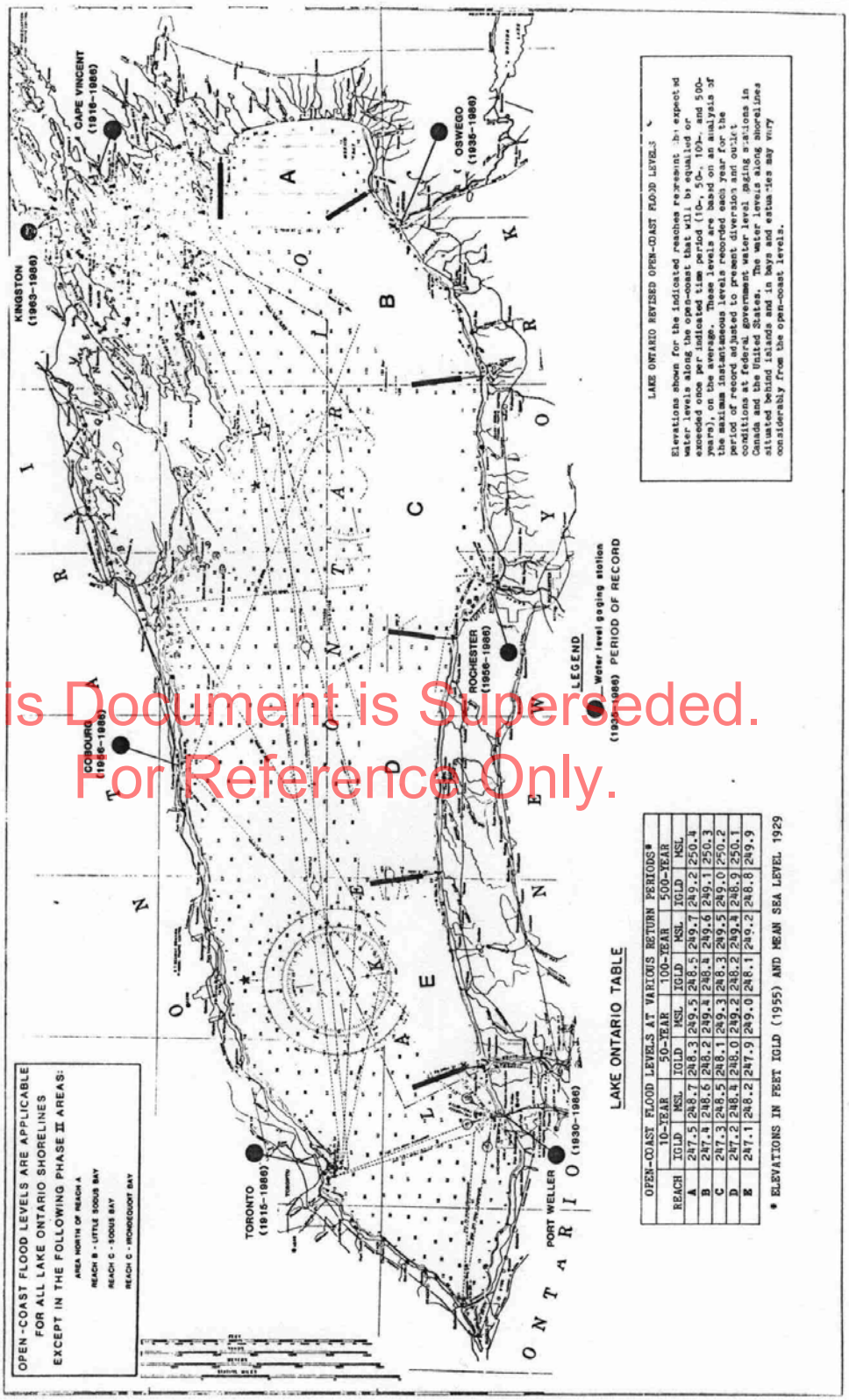


This Document is Superseded.
For Reference Only.

**Figure D-55. Lake Ontario Table and Map of Open Coast Flood Levels (USACE, 1988).**

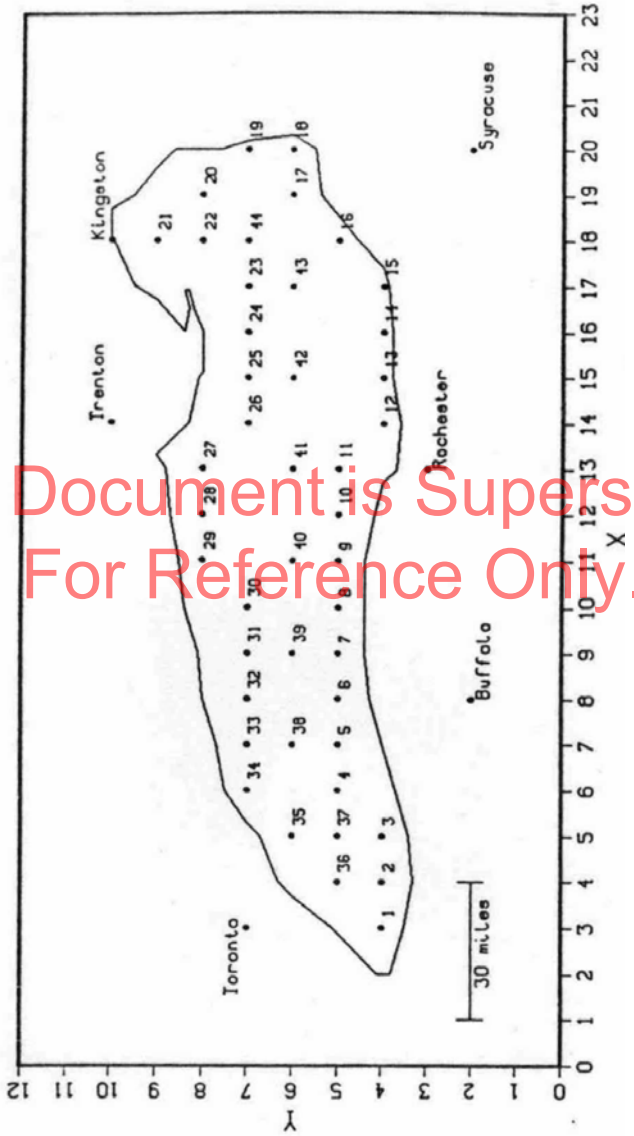


**Figure D-56. Station Location Map for Lake Ontario Wave Information Stations.**

This Document is Superseded.
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**Table D-27. One-Half-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Ontario**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| ONT-04 | 2.7 | -- |
| ONT-06 | 2.9 | 6.7 |
| ONT-07 | 3.0 | 7.1 |
| ONT-11 | 3.2 | 7.1 |
| ONT-14 | 2.6 | -- |
| ONT-17 | 3.2 | 7.1 |
| ONT-21 | 2.4 | 5.9 |

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## D.4 Wave Elevation Determination and V Zone Mapping: Pacific Ocean

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

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## D.5 Erosion Hazard Study, Identification, and Mapping

No FEMA guidance documents have been published for erosion hazard studies and mapping. Guidance is to be developed based on new or existing methodologies recommended by FEMA and coastal states for erosion hazard studies and mapping in all coastal areas.

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This Document is Superseded.
For Reference Only.

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Map MODERNIZATION

Federal Emergency Management Agency

FEMA's Flood Hazard Mapping Program

# Guidelines and Specifications for Flood Hazard Mapping Partners

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## *Appendix D: Guidance for Coastal Flooding Analyses and Mapping*

FEDERAL EMERGENCY MANAGEMENT AGENCY

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# Appendix D

# Guidance for Coastal Flooding Analyses and Mapping

## D.1 General Guidance

A variety of analytical methodologies may be used to establish Base Flood Elevations (BFEs) and floodplains throughout coastal areas of the United States. These methodologies are too voluminous to be included in these Guidelines. This Appendix itemizes references for the methodologies currently in use by FEMA for specific coastal flood hazards, provides general guidance for documentation of a coastal flood hazard analysis, specifies flood hazard analysis procedures for the Great Lakes coasts, and outlines intermediate data submissions for coastal flood hazard analyses with new storm surge modeling and revised stillwater flood level (SWFL).

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### D.1.1 Coastal Flood Hazard Analysis Methodologies

The publications cited below were prepared for, and are available from, FEMA, or they are used to prepare a coastal flood hazard assessment and establish BFEs. The publications prepared for FEMA will be provided to the Mapping Partners responsible for performing coastal flood hazard analyses. The Mapping Partners responsible for final production of Flood Insurance Studies (FISs) for the Atlantic Ocean, Gulf of Mexico and Great Lakes shall obtain copies of the published data used to prepare the coastal flood hazard analyses and establish BFEs, and shall be familiar with the use and application of the information presented in the publications cited below. Mapping Partners responsible for final production of FISs for the Pacific Ocean coastal areas shall consult with the appropriate FEMA Regional Project Officer (RPO) to determine the appropriate methodologies that shall be followed.

This Document is Superseded.
For Reference Only.

**Northeaster Flooding**

Stone & Webster Engineering Corporation, "Development and Verification of a Synthetic Northeaster Model for Coastal Flood Analysis," 1978.

U.S. Department of the Army, Corps of Engineers, New England Division, Hydraulics and Water Quality Section, "Tidal Flood Profiles, New England Coastline," September 1988.

**Hurricane Flooding**

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States (NWS 38),* April 1987.

Federal Emergency Management Agency, *FEMA Coastal Flooding Storm Surge Model*, Volumes 1, 2, and 3, August 1988.

**Pacific Northwest Storm Flooding**

CH2M HILL, Inc., "Determination of Flood Levels on the Pacific Northwest Coast for Federal Insurance Studies," *Journal of Hydraulics Division, ASCE*, D. E. Dorratcague, J. H. Humphrey, and R. D. Black, 1977, Vol. 103, 73–81.

U.S. Department of the Army, Corps of Engineers, Pacific Ocean Division, *Manual for Determining Tsunami Runup on Coastal Area of Hawaii*, August 1978.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Technical Report H-80-16, *Tsunami-Wave Elevation Predictions for American Samoa*, September 1980.

**Tsunami Flooding**

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Technical Report H-77-16, *Tsunami-Wave Elevations, Frequency of Occurrence for the Hawaiian Islands*, August 1977.

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**Great Lakes Mapping of Coastal Flooding Areas**

U.S. Department of the Army, Corps of Engineers, *Revised Report on Great Lakes Open-Coast Flood Levels*, *Phases I and II*, April 1988.

U.S. Department of the Army, Corps of Engineers, *Great Lakes Wave Runup Methodology Study*, June 1989.

Federal Emergency Management Agency, *Guidelines for Great Lakes Wave Runup Computation and Mapping*, June 1991.

Dewberry & Davis, *Basic Analyses of Wave Action and Erosion with Extreme Floods on Great Lakes Shores,* Draft Report, October 1995.

Federal Emergency Management Agency, *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping – Great Lakes,* Draft Report, August 1996.

**Mississippi River Delta Flooding**

Joseph N. Suhayda, *Attenuation of Storm Waves over Muddy Bottom Sediments*, August 1984.

**Wave Height and Runup Analyses**

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

Federal Emergency Management Agency, *Assessment of Current Procedures Used for the Identification of Coastal High Hazard Areas (V Zones)*, September 1986.

Federal Emergency Management Agency, *Basis of Assessment Procedures for Dune Erosion in Coastal Flood Insurance Studies*, January 1989.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center, WIS Report 19, *Hurricane Hindcast Methodology and Wave Statistics for Atlantic and Gulf Hurricanes from 1956-1975*, April 1989.

Federal Emergency Management Agency, *Wave Height Analysis for Flood Insurance Studies (Technical Documentation for WHAFIS Program Version 3.0)*, September 1988, amended with software, July 1989.

Federal Emergency Management Agency, *Wave Runup Model Version 2.0 (RUNUP 2.0), 1991*.

This Document is Superseded.
For Reference Only.

U.S. Department of the Army, Corps of Engineers, *Shore Protection Manual, Volumes I and II,* 1984.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, *Automated Coastal Engineering System*, Version 1.07, September 1992.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center, WIS Report 20, *Southern California Hindcast Wave Information*, December 1992.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center, WIS Report 30, *Hindcast Wave Information for the U.S. Atlantic Coast*, March 1993.

**Evaluation of Coastal Structures**

U.S. Department of the Army, Corps of Engineers, *Shore Protection Manual, Volumes I and II,* 1984.

U.S. Department of the Army, Corps of Engineers, *Design of Coastal Revetments, Seawalls and Bulkheads*, April 1985.

U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Technical Report CERC-89-15, *Criteria for Evaluating Coastal Flood Protection Structures*, December 1989.

**Atlantic and Gulf Mapping of Coastal Areas**

Federal Emergency Management Agency, *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping*, Final Draft, March 1995.

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## D.1.2 Study Documentation

Mapping Partners responsible for producing coastal FISs must document fully the coastal flood hazard determination for each study. This documentation shall identify the methodology employed as well as the computational approach and the input data used in the calculation of the coastal flood elevations. The technical specifications under which all coastal FISs will be documented are provided in the various internal and public FEMA reports outlining the approved coastal storm surge elevation methodology that are referenced in Subsections D.1.1 and D.1.4. These reports include algorithms, computer codes, guidelines for model use, and examples of model runs.

Although some of these reports provide relatively specific information on both the general procedures to be employed in processing the meteorological and hydrologic data, and the specifics of the hydrodynamic and windfield models to be employed, the reports contain no information on the application of the methodology to a particular coastal site. Therefore, the Mapping Partner responsible for performing a coastal study shall document the specific meteorological and hydrologic data, ocean bathymetry, shoreline characteristics, surface and bottom friction coefficients, and other parameters used in the particular model application. For this purpose, the Mapping Partner shall produce an engineering report for each coastal study.

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The purpose of the engineering report is to provide the detailed site-specific data needed by FEMA and the affected coastal communities to reconstruct or defend, on technical grounds, the study results. In general, the documentation shall include the input data; modeling approach; model parameter values; and all assumptions, decisions, and judgments that influence model outputs. The material to be included in the engineering report is summarized in the subsections below. Although the emphasis is on coastal studies incorporating storm surge models, Mapping Partners using other methods shall nonetheless adhere to the appropriate subsections. The Mapping Partner performing a coastal study shall obtain RPO approval for any deviations from the requirements documented in these Guidelines.

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### D.1.2.1 Introductory Material

In the first section of the engineering report, the Mapping Partner shall describe the geographic setting of the study site, discuss the local surge-producing climatology of both tropical and

extratropical storms, and provide a history of extreme storm surges. The Mapping Partner shall also report on unique aspects of each component of the stillwater flood elevation (SWEL) that was investigated (e.g., inverted barometer setup, wind transport, astronomical tide level, pre-surge anomaly, wave action, and abnormal hydrological conditions). The Mapping Partner also shall include a short discussion of the coastal study results and how they will be used in producing the Flood Insurance Rate Map (FIRM).

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### D.1.2.2 Outline of Methodology

In the second section of the engineering report, the Mapping Partner shall provide an outline of the basic technical approach employed in the study. Topics to be covered include identification of the storm (wind) model, the hydrodynamic model, and the statistical procedure used to determine flood frequencies. The purpose of this section is to outline the relationship between the technical material to be covered in the main body of the engineering report and the basic methodological approach used in the study. This outline should be logically organized and sufficiently complete so that the detailed documentation that follows can be easily read and understood.

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### D.1.2.3 Storm Climatology and Storm Windfield Methodology

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In this section of the engineering report, the Mapping Partner shall:

- Describe the basic climatological storm data used and the windfield methodology employed.
- Map, tabulate, and discuss in terms of local surge impact the storm paths used in the analysis.
- Tabulate and describe in written form the storm parameters (including central pressure deficit, radius to maximum wind, forward speed, shoreline crossing point, and shoreline crossing angle) used in the analysis.
- Identify sources of the basic data used to develop the storm climatology and the method used to sort the data and compare them with the National Weather Service (NWS) *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States (NWS 38)*.
- Describe the technique employed to determine the spatial/temporal distribution of storm occurrences (i.e., storms/nautical mile/year), derivation and discretization of storm intensity parameters, and exceedence probability distributions.
- Provide graphical presentation of the results, including an overlay with orientation of coast to storm path/direction.
- Provide a discussion of storm parameter independence and any unique storm model treatments.

- Give the exact equations used to parameterize the model windfield along with any unique values of all the appropriate coefficients and constants used. The windfield used in the analysis is a key component in the determination of the storm surge elevation.

- Include a diagram of the windfield model that gives the surface velocity structure as it changes radially outward from the storm center.

- Provide a comparative graph depiction of measured windfield(s) and modeled windfield, if available.

- Describe the method by which winds are reduced as the storm approaches land and moves inland in detail.

- Report the constants used in windspeed reduction.

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### D.1.2.4 Hydrodynamic Storm Surge Model

This section of the engineering report is to address the hydrodynamic storm surge model employed in performing the coastal study. The model used to calculate the surge elevation has been described in detail in various FEMA documents and need only be cited by reference. In this section of the engineering report, the Mapping Partner shall:

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- Report the unique model characteristics used for the study, including a discussion of the specific grid system and sub-grid systems employed, the grid used for bottom topography and shoreline, small-scale features such as harbors and barrier islands, and the location and conditions applied for the open boundaries to the grid.

- Describe and document the adjustment to land features to account for erosion.

- Describe and document the method used to determine average ground elevations and water depths within the cells of the grid system. This discussion should be augmented by diagrams that show the grid systems as computer listings of the grid data used in the actual model calculations.

- Describe the method used to relate windspeed and surface drag coefficient is to be described.

- Discuss the Manning's "n" values used in the calculation of bottom and overland friction and provide values in tabular form. This information will include a discussion of any sensitivity tests used to estimate these values in nearshore water. Nearshore bottom and overland friction is an important part of the overall analysis and, therefore, shall be described with care and sufficient detail.

- Provide a graphical depiction of the model cells and grid system as an overlay to the bathymetric charts and topographic maps covering the study area, annotated with the individual cell inputs for the grid system.

- Discuss the method by which barriers, inlets, and rivers have been treated.
- Explain the procedures used to determine inland flooding, including parameterization of local features and selection of the friction factors used for the terrain.

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### D.1.2.5 Calibration and Verification of Hydrodynamic Storm Surge Model

In this section of the engineering report, the Mapping Partner shall document the calibration and verification of the hydrodynamic surge model. Once the hydrodynamic storm surge model and grid have been set up, calibration and verification are performed. Calibration is done to determine the adjustable "tuning parameters" (e.g., Manning's "n", barrier overflow coefficients) and to validate the chosen grid schematization. Verification is used to validate the model and grid for situations other than the case used to calibrate the model. Sensitivity runs are used to make sure that small changes in the chosen grid and "tuning parameters," will not give rise to unacceptable large changes in the computed flood and tide levels. Calibration and verification computer runs compare computed results with observed water levels. Sensitivity runs compare computed results with other computed results.

When observed (or model simulation) data are employed to calibrate (or compare) hydrodynamic storm surge model results with other available studies, the Mapping Partner shall give a complete description of this calibration procedure (or model comparison), including a listing of measured and simulated tidal data. Calibration (and model comparison) is an important aspect of the model analysis; therefore, the Mapping Partner shall described these activities with sufficient detail and care to allow an independent reviewer to understand the exact procedures employed and the local historical records employed.

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### D.1.2.6 Statistical (Joint Probability) Methodology

If the joint probability method was used, the Mapping Partner shall summarize, map, and report the values and combinations used for storm parameters, annual storm density, spacing between storms, and the storm tracks used in the analysis in this section of the engineering report. In this section, the Mapping Partner also shall compare the information above with the probabilities reported in *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States (NWS 38)*. Specifically, the Mapping Partner shall:

- Note the total number of simulations.
- Summarize tidal elevation data, if used, in sufficient detail to remove any doubt as to the values used in the simulations.
- Describe the method by which the tidal elevation data are convoluted with surge data including tidal constants and tidal records.

- Describe storm occurrence rate or storm density, the definition of the storm region used to define storm density, and storm kinematics and intensity with respect to their use in the joint probability calculation.
- Report and discuss comparisons to long-term gage statistics.
- Describe and report adjustments to account for the combined probability of coastal and riverine flooding for each area where such an approach was taken.

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### D.1.2.7 Unique Computer Programs

Several different computer codes may be used in the wind, hydrodynamic, and joint probability analysis. Several basic computer programs have been listed in numerous FEMA reports. In this section of the engineering report, the Mapping Partner shall list and describe any modifications of these programs and special data inputs used in the study.

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### D.1.2.8 Wave Height, Runup, and/or Erosion Analysis

In this section of the engineering report, the Mapping Partner responsible for performing the coastal analysis shall reference the wave height, runup, and/or erosion analysis methodology used for the study. Specifically, the Mapping Partner shall:

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- Document fully any deviation or expansion of that approach.
- Describe the selection of input data, including a reference to source data and material.
- Document fully all erosion considerations.
- Include one or more transect location maps as appropriate.
- Include computer printout listings for input and output data as an appendix to the report, keyed to the transect location map(s).

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### D.1.2.9 References

In the final section of the engineering report, the Mapping Partner shall provide a complete list of technical references, including computer program references, indicating how to obtain copies of the exact program and the input data sources used in the analysis.

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## D.1.3 Great Lakes Wave Runup Computations and Mapping

Mapping Partners performing coastal studies for communities along the Great Lakes shoreline should use the wave runup analysis guidance in Section D.3. Section D.3 provides a wave runup study flow chart, the detailed study procedure steps, sample computations, and mapping policies. An overview of the coastal study procedures is presented below.

[February 2002]

### D.1.3.1 Wave Runup Calculation Procedures

The guidelines for Great Lakes wave runup calculations have emerged from methodologies recommended by the Detroit District of the U.S. Army Corps of Engineers (USACE) in the study report entitled *Great Lakes Wave Runup Methodology Study*. The figures and tables in Section D.3 have been drawn from various references cited in this USACE study report. Further guidance on the wave runup approach is included in Section D.3. Although this guidance is subject to change based on new information and methodology improvement, it provides the framework and information on the application of the methodologies.

Three types of shorelines are considered: a natural beach profile and two types of armored shoreline profiles (vertical wall and rock revetment). Therefore, three runup methodologies corresponding to the three shoreline types are employed. The flow of tasks begins with site profile data-gathering, tracks through various intermediate steps, such as the 1-percent-annual-chance flood level determination, and the calculation of the deep water and shallow water wave height, and ends with the wave runup determination for each type of shoreline.

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### D.1.3.2 Wave Runup Computation Steps and Sample Calculations

When the site location is identified, the Mapping Partner shall follow the step-by-step study procedures below to determine the maximum wave runup elevations to be used in coastal floodplain boundary delineations.

- Step 1. Profile Data Gathering
- Step 2. 1-percent-annual-chance Flood Level Determination
- Step 3. Offshore (Deep Water) Wave Height Determination
- Step 4. Nearshore (Shallow Water) $H_{mo}$, $H_s$, and $T_p$ Computation
- Step 5. Wave Runup Computation
- Step 6. Determination of Maximum Wave Runup Elevation

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#### D.1.3.3 Delineation and Mapping Policy

Six general policies and 12 specific-case mapping policies accompanied with illustration diagrams may be used in the coastal FIS map delineation for Great Lakes coastal communities. (See Section D.3 for detailed information.) Mapping Partners shall apply the general policies to all cases and the specific-case policy to a certain situation. Three types of shoreline profiles are typical in the Great Lakes region and are used to classify the cases:

- Beach profile with a natural dune system;
- Beach profile with a bluff system; and
- Beach profile with coastal structures.

For each type of shoreline profile, the Mapping Partner shall consider four separate cases, depending on the computed wave height profile, wave runup height, 1-percent-annual-chance stillwater level, and the predicted post-storm erosion profile. For other special cases that cannot be covered by the above policies, the Mapping Partner shall consult with the RPO.

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### D.1.4 Intermediate Data Submission for Coastal Flood Studies

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Coastal analyses involving storm surge modeling are highly specialized and complex and require a highly specialized review process. Experience has shown that attempting to make changes or corrections to coastal storm surge and wave height analyses after they have been run and mapped is not practical due to the time, cost, and contractual problems involved. Many questions and problems that arise during the review process could be answered or resolved much more readily if these issues were raised early in the study process. Therefore, FEMA has established intermediate data submission requirements to permit review of the Mapping Partner's progress on model development at appropriate milestones. The Mapping Partner performing the study shall submit the data to the reviewing Mapping Partner, as specified by the RPO, in accordance with the sequence discussed below.

The Mapping Partner will receive review comments within 30 days of the receipt of each data submission. The Mapping Partner performing the study shall establish a work plan so that the interim review does not cause any delay in the submission of the FIS Report draft and the maps reflecting the results of the coastal study.

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#### D.1.4.1 Before Storm-Surge Model Calibration Runs Are Made

The Mapping Partner performing the study shall submit the following to the reviewing Mapping Partner before calibration runs are made:

1. A large-scale map of the coastal area which delineates both the coarse grid basin(s) and fine grid basin(s);

2. A schematic of each basin (coarse grid and fine grid) showing sub-grid channel locations, widths, bed elevations, and proposed Manning's "n" values for each channel;

3. Historical evidence establishing the importance of various coastal flooding mechanisms (e.g., tropical and extratropical storms, rainfall and riverine events);

4. Basic data relating to the study area (e.g., documented storm erosion, available design analyses for shore protection or other coastal projects, historical shoreline changes);

5. Aerial photographs, coastal setback maps, and other maps used to determine more accurate topographic-bathymetric values and land cover features in the study area;

6. Table listing astronomical tide events and historical storms selected for use in model calibration and verification, and a plot showing the observed storm surge elevation against the predicted tide elevations;

7. Plots of exceedence probability vs. parameter value for the meteorological storm parameters that vary in the joint probability analysis, as developed for the study area following *NWS 38*, with documentation to include a tabular presentation of all meteorological storm parameter data used in development of the exceedence probability curves; and

8. Table showing storm parameter values and assigned probabilities.

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### D.1.4.2 Before Operational Storm Surge Runs Are Made

The Mapping Partner performing the study shall submit the following to the reviewing Mapping Partner before operational storm surge runs are made:

1. A map of each basin (coarse grid and fine grid) showing water depths, ground elevations, and Manning's "n" values for each grid cell;

2. A map of each basin (coarse grid and fine grid) showing barrier locations, barrier heights, barrier widths, barrier Manning's "n" values, location of inlets cutting through barriers, inlet widths, inlet bed elevations, inlet Manning's "n" values and inlet entrance and loss coefficients;

3. A computer printout listing of the water depth, ground elevations, Manning's "n" values, barrier and inlet input, and the sub-grid channel input, and any other input data used in the calibration and verification runs and that will be used in the production runs;

4. Description of sensitivity runs used to optimize model parameters for the study area, for example, in final choices of Manning's "n" values;

5. Tide and storm calibration results (including extreme water elevations and time histories) showing computed results and a comparison of these with observations where such observations are available;

6. Grid overlay and work maps used in storm surge analyses for all fine and open-coast grid basins; and

7. Written documentation, including justification, of any modifications made to the standard FEMA storm surge methodology and a listing of the computer source code annotated where the modifications were made.

The work maps listed in No. 6 above should generally be the 7.5-minute series U.S. Geological Survey quadrangle maps and the hydrographic charts that were used to gather topographic, bathymetric, roughness, and other input data for the storm surge calculations. The Mapping Partner performing the study shall draw the grid pattern on the maps or use one or more transparent overlays registered to the work map(s) to indicate where the grid cells fall with respect to various map features. The Mapping Partner also shall indicate the location and extent of each wave transect on the overlays or work maps.

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### D.1.4.3 Before Operational Wave Elevation Determination Are Made

The Mapping Partner performing the study shall submit the following to the reviewing Mapping Partner before operational wave elevation determinations are made:

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1. Documentation of conclusions on the interaction between storm surge and astronomical tide;

2. Output of PROBS program for all open coast and fine grid basins;

3. Grid showing 10-, 2-, 1-, and 0.2-percent-annual-chance SWFLs for each open coast and fine grid basin; and

4. Location map of proposed transects to be used in the wave elevation determination analyses.

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### D.1.4.4 Before Wave Elevation Determinations Are Mapped

The Mapping Partner performing the study shall submit a copy of all wave height and wave runup transect computations, and all modeling assumptions to the reviewing Mapping Partner before wave elevations and resulting BFEs are mapped.

[February 2002]

## D.2 Wave Elevation Determination and V Zone Mapping: Gulf of Mexico and Atlantic Ocean

The mapping of V Zones under the NFIP began in the early 1970s. The objective was to identify hazardous coastal areas in a manner consistent with the original regulatory definition of coastal high hazard areas as an "area subject to high velocity waters, including but not limited to hurricane wave wash." The initial technical guidance for identifying V Zones was provided in a June 1973 report by the USACE, Galveston District entitled *General Guidelines for Identifying Coastal High Hazard Zone, Flood Insurance Study - Texas Gulf Coast Case Study*, prepared by the U.S. Army Corps of Engineers (USACE), Galveston District (1973). The USACE report identified a breaking wave height of 3 feet as critical in terms of causing significant structural damage and illustrated procedures for mapping the limit of this 3-foot wave (V Zone) in two distinct situations along the Texas coast: undeveloped areas and highly developed areas.

In June 1975, the USACE issued a follow-up report entitled *Guidelines for Identifying Coastal High Hazard Zones* which maintained the basic recommendations contained in the 1973 report for identifying V Zones in undeveloped and developed areas; however, the 1975 report also included guidance for determining effective fetch lengths, a technical discussion justifying the 3-foot wave height criterion for V Zones, an abbreviated procedure for V Zone mapping in undeveloped areas, an expanded discussion of V Zone mapping in developed areas, and historical accounts of several severe storms that have impacted developed areas along the Atlantic and Gulf coasts.

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Between 1975 and 1980, the Federal Government (U.S. Department of Housing and Urban Development until 1978 and FEMA thereafter) published FIRMs with V Zones for approximately 270 communities along the Atlantic and Gulf coasts using the USACE guidance for V Zone mapping. During this period, the procedures for determining and delineating V Zones in developed areas differed among studies. At that time, the regulatory BFEs, for both insurance and construction purposes, were the 1-percent-annual-chance stillwater elevations (SWELs), which consisted of the astronomical tide and storm surge caused by low atmospheric pressure and high winds. Although V Zones were identified, the increase in water-surface elevation due to wave action was not included. The Federal Government recognized that this practice did not accurately represent the flooding hazard along the open coast, but an adequate method for estimating the effects of wave action, applicable to most coastal communities, was not readily available at the time.

In 1976, the National Academy of Sciences (NAS) was asked to provide recommendations about how calculations of wave height and runup should be incorporated in FISs for Atlantic and Gulf coast communities to provide an estimate of the extent and height of stormwater inundation having specified recurrence intervals. The NAS concluded that the prediction of wave heights should be included in FISs for coastal communities and provided a methodology for the open coast and shores of embayments and estuaries on the Atlantic and Gulf coasts. The 1977 report documenting the NAS findings, *Methodology for Calculating Wave Action Effects Associated with Storm Surges* included means for taking into account varying fetch lengths, barriers to wave transmission, and regeneration of waves likely to occur over flooded land areas. NAS did not

address the extent and elevation of wave runup, amount of barrier overtopping, and coastal erosion.

In 1979, FEMA adopted the NAS methodology. In 1980, FEMA issued *Users Manual for Wave Height Analysis*, which was subsequently revised in February 1981. FEMA also introduced a computer program, Wave Height Analyses for Flood Insurance Studies (WHAFIS), in 1980. With WHAFIS, FEMA initiated a large effort to incorporate the effects of wave action on the FIRMs for communities along the Atlantic and Gulf coasts.

Along the New England coast with its very steep shore, the NAS methodology proved to be insufficient. Structures that were shown as being outside of the SFHA on effective FIRMs experienced considerable wave damage from storms, most notably the northeaster of February 1978, a near 1-percent-annual-chance flood event. The need to account for the effects of wave runup was recognized. In 1981 FEMA approved a methodology that determined the height of wave runup landward of the stillwater line. Stone & Webster Engineering Corporation developed the methodology in November 1981. In 1987, FEMA modified its computer model for runup elevations slightly to increase the convenience of preparing input conditions. In 1990, FEMA modified the model again to improve computational procedures and application instructions to conform to the best available guidance on wave runup (Dewberry & Davis, 1990).

Two additions were made to the NAS methodology in 1984 to account for coastal situations involving either marsh grass or muddy bottoms. The NAS methodology did not account for flexible vegetation; in particular, marsh plants. Experts surmised that the motion of submerged marsh plants absorbed wave energy, reducing wave heights. In 1984, a FEMA task force examined this phenomenon in detail and developed a methodology that adjusted the wave height to reflect energy changes resulting from the flexure of various types of marsh plants and the wind, water, and plant interaction (FEMA, 1984). FEMA incorporated the new methodology into WHAFIS.

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The muddy bottom situation occurs only at the Mississippi Delta in the United States. The Mississippi River has deposited millions of tons of fine sediments into the Gulf of Mexico to form a soft mud bottom in contrast to the typical sand bottom of most coastal areas. This plastic, viscous bottom deforms under the action of surface waves. This wave-like reaction of the bottom absorbs energy from the surface waves, thus reducing the surface waves. A methodology was developed for FEMA to calculate the wave energy losses due to muddy bottoms (Suhayda, 1984). Waves in the offshore areas are tracked over the mud bottom, resulting in lower incident wave heights at the shoreline. This is a phenomenon unique to the Mississippi Delta, and FEMA has not incorporated the methodology into WHAFIS.

In 1988, FEMA upgraded WHAFIS to incorporate revised wave forecasting methodologies described in the 1984 Edition of the USACE *Shore Protection Manual* (USACE, 1984) and to compute an appropriately gradual increase or decrease of SWELs between two given values (FEMA, September 1988).

In the performance of wave height analyses and the preparation of FISs, erosion considerations were left to the judgment of FEMA contractors. Coastal erosion was to be considered a hazard

when there was historical evidence of erosion from previous storms, but prior to 1986, objective procedures for treating erosion were not available. Consequently, some shorefront dunes were designated as stable barriers to flooding and some were not. In 1986, FEMA initiated studies aimed at providing improved erosion assessments in FISs for coastal communities.

In response to criticisms indicating a significant underestimation of the extent of Coastal High Hazard Areas, FEMA undertook an investigation to reevaluate V Zone identification and mapping procedures. The resulting report, entitled *Assessment of Current Procedures Used for the Identification of Coastal High Hazard Areas (V Zones)* presented a number of recommendations to allow for more realistic delineation of V Zones and to better meet the objectives of the NFIP for actuarial soundness and prudent floodplain development (FEMA, 1986). One recommendation was for full consideration of storm-induced erosion and wave runup in determining BFEs and mapping V Zones. As part of its investigation, FEMA performed a study of historical cases of notable dune erosion. In this quantitative analysis, field data for 30 events (later increased to 38 events) yielded a relationship of erosion volume to storm intensity as measured by flood recurrence interval. For the 1-percent-annual-chance storm, FEMA determined that, to prevent dune breaching or removal, an average cross-sectional area of 540 square feet is required above the SWEL and seaward of the dune crest. That standard for dune cross section has a central role in erosion assessment procedures.

The USACE Coastal Engineering Research Center (CERC) performed a study of the available quantitative erosion models for FEMA (Birkemeier, Kraus, Scheffner, & Knowles, 1987). USACE determined that only empirically based models produce reasonable results with a minimum of effort and input data, that each available model for simple dune retreat has certain limitations, and that dune overwash processes are poorly documented and unquantified. After further investigations, FEMA decided to employ a set of extremely simplified procedures for objective erosion assessment (FEMA, November 1988). These procedures have a direct basis in documented effects due to extreme storms and are judged appropriate for treating dune erosion in FISs for coastal communities.

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As the official basis for treating flood hazards near coastal sand dunes, FEMA published new rules and definitions in the *Federal Register* that became effective on October 1, 1988. FEMA included the following revised definition in Section 59.1 of the NFIP regulations:

> *Coastal high hazard area* means an area of special flood hazard extending from offshore to the inland limit of a primary frontal dune along an open coast and any other area subject to high velocity wave action from storms or seismic sources.

FEMA also added a clarification of this matter, a definition of primary frontal sand dune, in Section 59.1:

> *Primary frontal dune* means a continuous or nearly continuous mound or ridge of sand with relatively steep seaward and landward slopes immediately landward and adjacent to the beach and subject to erosion and overtopping from high tides and waves during major coastal storms. The inland limit of the primary frontal dune occurs at the point where there is a distinct change from a relatively steep slope to a relatively mild slope.

FEMA also included a new section in Part 65 of the NFIP regulations, identifying a cross-sectional area of 540 square feet as the basic criterion to be used in evaluating whether a primary frontal dune will act as an effective barrier during the 1-percent-annual-chance flood. Another consideration is the documented historical performance of coastal sand dunes in extreme local storms.

In 1989, USACE completed a review for the NFIP regarding coastal structures as protection against the 1-percent-annual-chance flood (Walton, Ahrens, Truitt, & Dean, 1989). Predictions of wave forces, wave overtopping, and wave transmission for commonly occurring structures were among technical topics addressed in the USACE report. The guidelines in this Appendix incorporate procedural criteria recommended by the USACE for evaluating structural stability.

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## D.2.1 Organization and Overview

Figure D-1 presents a flowchart of appropriate procedures for defining coastal hazards of the 1-percent-annual-chance flood. Fundamental aspects of the 1-percent-annual-chance flood are addressed in the following sequence:

1. SWEL,
2. Accompanying wave conditions,
3. Stability of coastal structures,
4. Storm-induced erosion,
5. Wave runup and overtopping, and
6. Overland wave heights.

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Determination of SWELs usually involves detailed statistical analyses, but added effects due to surface wave action are treated by simplified deterministic methodologies. This strategy avoids any potential complications due to conditional probabilities for simultaneous flooding effects. The sequence for treating these effects is entirely consistent in principle; for example, added wave effects are not resolved within the equations commonly used to simulate coastal storm surges and establish SWEL for the 1-percentannual-chance flood.

The order indicated in Figure D-1 for activities, assessments, and analyses also outlines the organization of topics treated in these guidelines. Subsection D.2.2 provides general data requirements for conducting a coastal study, including that data needed as input to computer models. Subsection D.2.3 discusses requisite evaluation of coastal structures potentially providing wave and/or flood protection. Subsection D.2.4 considers the erosion assessment needed to project the configuration of the shore profile during the 1-percent-annual-chance flood. Subsection D.2.5 treats wave runup, wave setup, and overtopping occurring at shore barriers in flood conditions. Subsection D.2.6 addresses the analysis of nearshore wave heights

and wave crest elevations relevant to a study. Each of these sections provides guidance on the models and procedures for treating individual transects at a study site.

FEMA has established specific models and procedures for the evaluation of shore structures, erosion, wave runup, and wave heights in the determination of coastal flood hazards. For many coastal areas, all four topics must be considered for an adequate treatment; for other coastal areas, application of only one or two of the FEMA methodologies may be required to produce reasonable results. Table D-1 lists some typical shoreline types and the models that should be used for them.

**Table D-1. Model Selection for Typical Shorelines**

| TYPE OF SHORELINE | MODELS TO BE APPLIED | | |
|---|---|---|---|
| | EROSION | RUNUP | WHAFIS |
| Rocky bluffs | | x | x |
| Sandy bluffs, little beach | x | x | x |
| Sandy beach, small dunes | x | | x |
| Sandy beach, large dunes | x | x | x |
| Open wetlands | | | x |
| Protected by rigid structure | | x | x |

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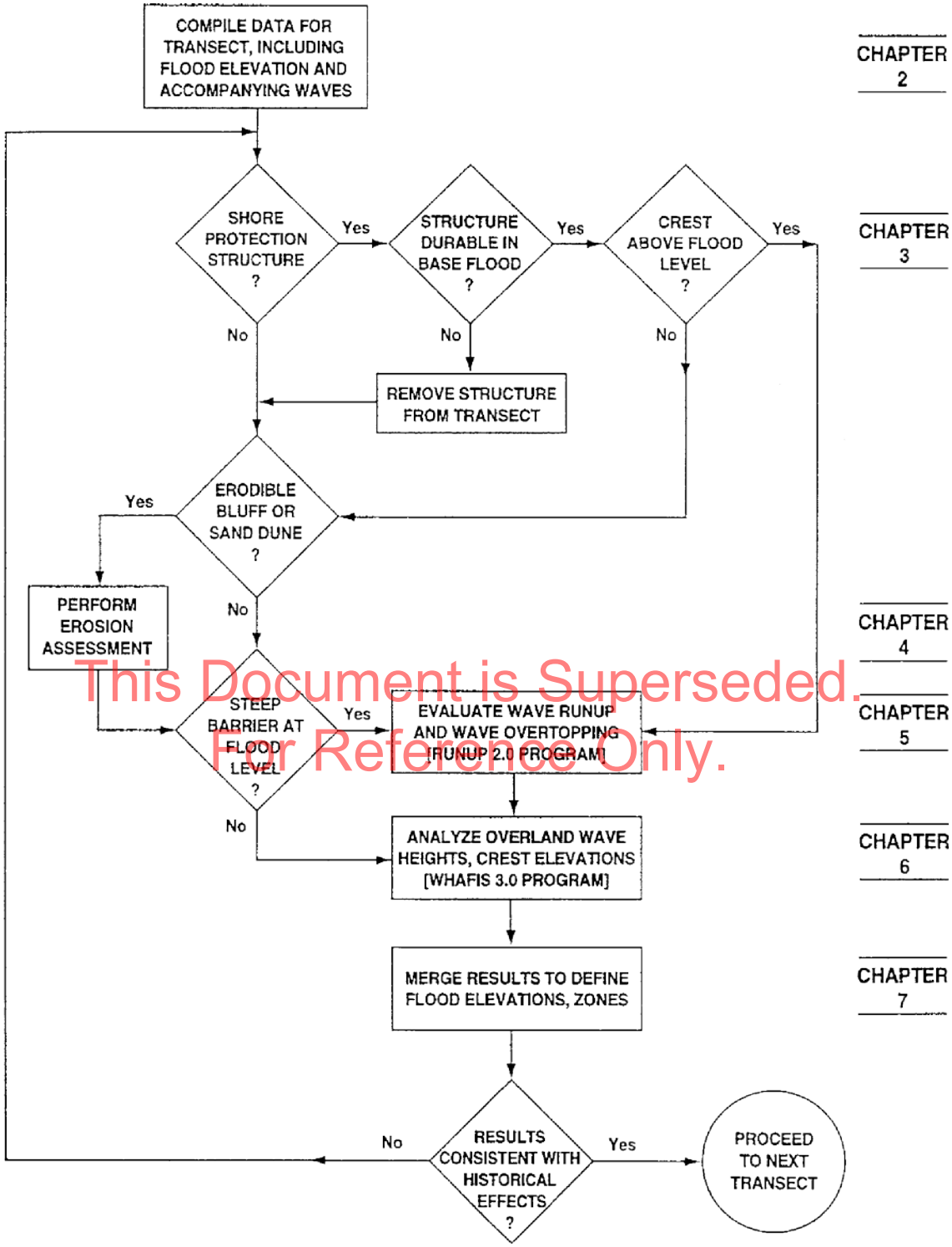


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**Figure D-1. Procedural Flowchart for Defining Coastal Flood Hazards**

The remaining material in these guidelines adopts a more comprehensive view toward completion of an FIS. Subsection D.2.7 addresses the integration of basic results into a coherent map for flood elevations and hazard zones. Subsection D.2.8 defines required documentation of the process, decisions, and data used in determining coastal flood hazards for a community. For consistency with the NFIP and compatibility with FISs, these guidelines use standard English units for all variables.

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## D.2.2 Data Requirements for Coastal Flood Hazard Analyses

To conduct a study for a coastal community, the Mapping Partner performing the study shall first collect the wide variety of quantitative data and other site information required in ensuing analyses. This subsection describes how coastal flood elevations and boundaries are determined, including an outline for the storm expected to cause the 1-percent-annual-chance flood, and characteristics of nearshore seabed through upland regions. Some data are directly input to computer models of flood effects, and other data are used to interpret and integrate the calculated results.

Each computer model of a separate flood effect is executed along transects, which are cross sections taken perpendicular to the mean shoreline to represent a segment of coast with similar characteristics. Thus, collected data are compiled primarily for transects, in turn situated on work maps at the final scale of the FIRM. Work maps are used both to locate and develop the transects, and to interpolate and delineate the flood zones and elevations.

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Aside from needed quantitative information, the Mapping Partner shall collect descriptions of previous flooding and the community in general to aid in the evaluation of flood hazards and for inclusion in the FIS Report. The Mapping Partner shall start data collection at the community level and proceed with county, state, and Federal agencies. The Mapping Partner also shall contact private firms specializing in topographic mapping and/or aerial photography, following up suggestions provided by government agencies.

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### D.2.2.1 Stillwater Elevations

The Mapping Partner shall determine the SWELs in a rational, defensible manner and shall not include contributions from wave action either as a result of the mathematics of the predictive model or of the data used to calibrate the model. Only the 1-percent-annual-chance SWEL is required for the coastal analyses, although 10-, 2-, and 0.2-percent-annual-chance elevations are provided in the FIS Report, and the 0.2-percent-annual-chance floodplain boundary is mapped on the FIRM.

SWELs may be defined by statistical analysis of available tide gage records or by calculation using a storm surge computer model. A minimum of 20 years of recorded tide data is needed if the SWEL is to be based on tide gage records alone. Measured tide levels are preferred over

synthetic models provided they have a significant period of continuous record over 20 years and can accurately represent the geographic area of the study. FEMA has available a self-contained hurricane storm surge model that can provide flood elevations (FEMA, August 1988) and a synthetic northeaster model that simulates the wind and pressure fields of an extratropical storm for input to a storm surge computer model (Stone & Webster Engineering Corporation, 1978). The Mapping Partner shall use these computer models for complex shorelines where gage records are limited, nonexistent, or non-representative, and usually indicate appreciable variations in flood elevations within a community. FEMA also has specified procedure and documentation for coastal flood studies using a storm surge model, as presented previously in Subsections D.2.2, D.2.3 and D.2.4. Of particular importance here, the surge model study can provide winds and water levels over time likely with the 1-percent-annual-chance flood.

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### D.2.2.2 Selected Transects

The Mapping Partner shall locate transects with careful consideration given to the physical and cultural characteristics of the land so that they will closely represent conditions in their locality. The transects are to be placed closer together in areas of complex topography, dense development, unique flooding, and where computed wave heights and runup may be expected to vary significantly. Wider spacing may be appropriate in areas having more uniform characteristics. For example, a long stretch of undeveloped shoreline with a continuous dune or bluff having a fairly constant height and shape, and similar landward features may require a transect only every 1 to 2 miles, whereas a developed area with various building densities, protective structures, and vegetation cover may require a transect every 1,000 feet.

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Good judgment exercised in placing required transects will avoid excessive interpolation of elevations between transects, while also avoiding unnecessary study effort. In areas where runup may be significant, the proper location of transects will be governed by variations in shore slope or gradient. On coasts with sand dunes, the Mapping Partner shall site transects according to major variations in the dune geometry and the upland characteristics. In other areas where dissipation of wave heights may be most significant to the computation of flood hazards, the Mapping Partner shall base transect location on variations in land cover: buildings, vegetation, and other factors. Generally speaking, the Mapping Partner shall site a separate transect at each flood protection structure. However, if areas with similar characteristics are scattered throughout a community and have the same SWEL, the Mapping Partner may apply the results from one transect at various locations within this common area. This should be done only after careful consideration is given to topographic and cultural features to assure the accurate representation of the coastal hazards.

The Mapping Partner shall locate the transects on the work map with the input data compiled on a separate sheet for each transect. The data for the transect are not taken directly along the line on the work map; they are taken from the area, or length of shoreline, to be represented by the transect so that the input data depict average characteristics of the area. Because of this, the Mapping Partner may find it is useful to divide the work map into transect areas for data compilation.

### D.2.2.3 Topography

The topographic data must have a contour interval no greater than 5 feet or 1.5 meters. FEMA does not require more detailed information such as spot elevations or a smaller contour interval, although they can be useful in the definition of the dune or bluff profile and in the delineation of floodplain boundaries. The topographic data, usually in the form of maps, must be recent and reflect current conditions or, at a minimum, conditions at a clearly defined time. Transects need not be specially surveyed unless available topographic data are unsuitable or incomplete. The Mapping Partner shall examine the topographic data to confirm that the information to be used in the analysis and mapping represents the actual planimetric features that might affect identification of the coastal hazards.

If possible, the Mapping Partner shall field-check shore topography to note any changes due to construction, erosion, coastal engineering, and other factors. The Mapping Partner shall document any significant changes with location descriptions, drawings, and/or photographs. The community, county, and state are usually the best sources for topographic data. The Mapping Partner shall examine USGS 7.5-minute series topographic maps. The USGS maps may have a 5-foot contour interval; if not, they are still often useful as reference or base maps.

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### D.2.2.4 Land Cover

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The land-cover data include information on buildings and vegetation. Stereoscopic aerial photographs can provide the required data on structures and some of the data on vegetation. The Mapping Partner shall ensure that aerial photographs are not more than 5 years old unless they can be updated by surveys. Local, county, or state agencies may have the coastline photographed on a periodic basis, and may provide photographs or permission to obtain them from their source.

Aerial photographs can provide the required data on tree- and bush-type vegetation. However, although they are useful in identifying areas of grass-like vegetation, they cannot identify specific types. National Wetland Inventory maps from the U.S. Fish and Wildlife Service and color infrared aerial photographs can provide some more specific data required for marsh plants. Ground-level photographs are also useful in providing information on plants. State offices of coastal zone management, park and wildlife management, and/or natural resources should be able to provide information. The Mapping Partner also may contact local universities with coastal studies and/or Sea Grant programs. The Mapping Partner may conduct field surveys in lieu of the above sources, but are more cost effective when used only to supplement or verify data obtained from these sources.

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### D.2.2.5 Bathymetry

The Mapping Partner may acquire bathymetric data from National Ocean Service nautical charts, although any reliable source may be used. The bathymetry must extend far enough offshore to include the breaker location for the 1-percent-annual-chance flood; although that depth may not be exactly known during the data collection phase, the Mapping Partner may assume that a mean water depth of 40 feet will encompass all typical breaker depths. Bathymetry further offshore also may be useful in interpreting likely differences between nearshore and offshore wave conditions and necessary where offshore waves are more readily specified.

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### D.2.2.6 Storm Meteorology

The 1-percent-annual-chance flood elevations represent a statistical summary and likely do not correspond exactly to any particular storm event. However, the meteorology of storms expected to provide approximate realizations of the 1-percent-annual-chance flood can be useful information in deciding recurrence intervals for historical events and in assessing wave characteristics likely associated with the 1-percent-annual-chance flood. An important distinction of the flood source from Delaware to Maine is whether the 1-percent-annual-chance flood is more likely to be caused by a hurricane or by a Northeaster. The Mapping Partner shall establish this distinction in the course of defining the SWELs, because time history of water levels can be radically different in the two possible cases (see Figure D-2).

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For a Northeaster, commonly a winter storm occurring between October and March, sustained winds seldom reach much above 60 mph, storm surge has relatively modest magnitude, and surge coincidence with spring high tides is usually required to attain the 1-percent-annual-chance SWEL. Extreme storms that occurred with lower tides can indicate wind and wave conditions also likely to accompany the 1-percent-annual-chance flood. Thus, the Mapping Partner can assemble a fair amount of pertinent historical evidence regarding expected meteorological conditions for the 1-percent-annual-chance flood arising from an extratropical storm. The dominant conditions include speed and duration of sustained winds, along with the storm size controlling fetch along which waves may be generated.

Where hurricanes are of primary importance, the 1-percent-annual-chance flood is likely associated with central pressure deficits having exceedance probabilities between 5 and 10 percent (FEMA, August 1988). That description generally corresponds to a major hurricane, where sustained winds exceed 120 mph. Other meteorological characteristics are likely to be fairly typical for the study area and may be determined using the hurricane climatology documented in *Hurricane Climatology for the Atlantic and Gulf Coasts of the United States* (Ho, Su, Hanevich, Smith, & Richards, 1987). That guidance includes localized probabilities for central pressure deficit, radius to maximum winds, and speed and direction of storm motion.

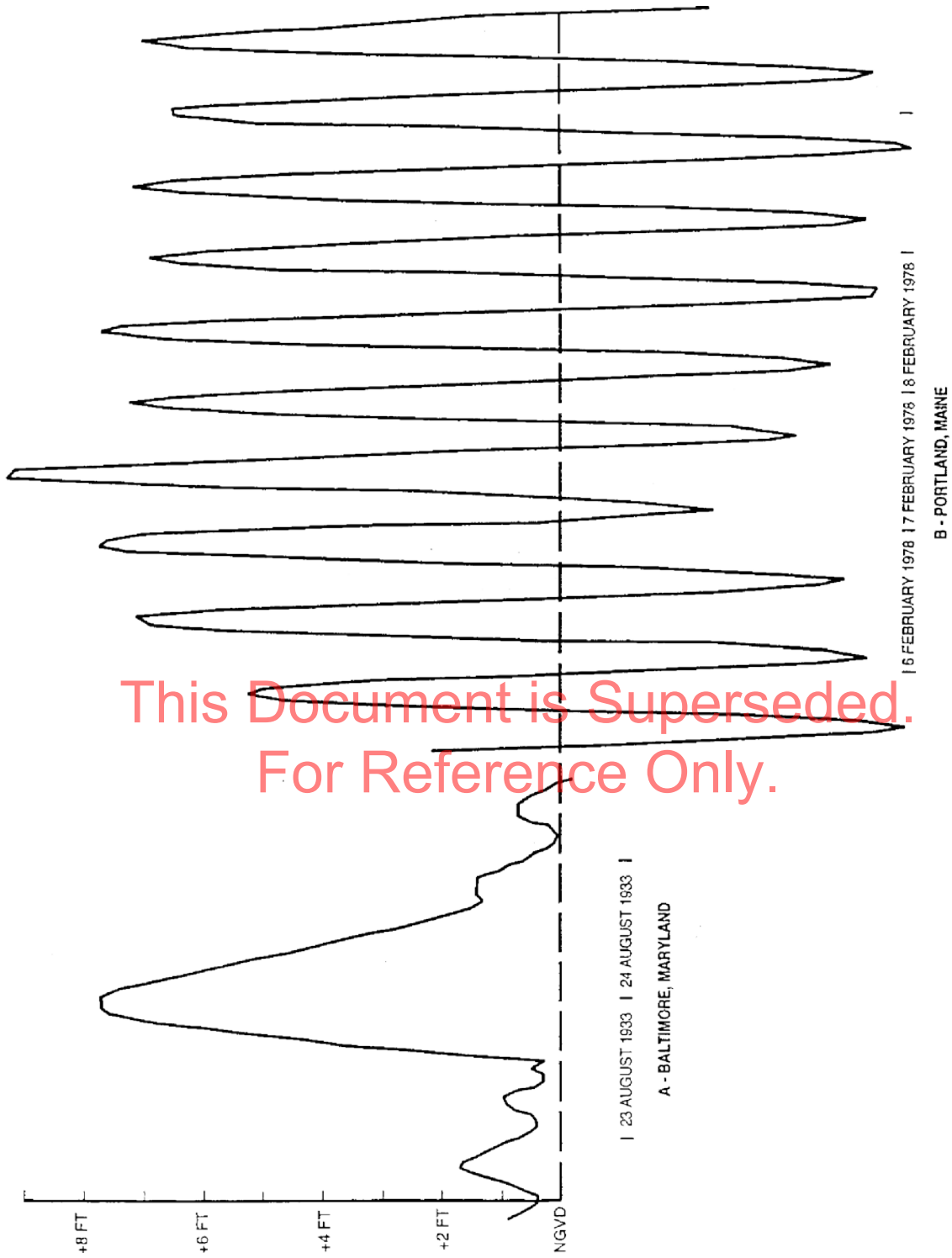


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**Figure D-2. Gage Records of Floods Peaking near the Local 1-Percent-Annual-Chance SWELs, Caused by, A- a Hurricane; and B- an Extratropical Storm**

### D.2.2.7 Storm Wave Characteristics

The basic presumption in conducting coastal wave analyses is that wave direction must have some onshore component, so that wave hazards occur coincidentally with the 1-percent-annual-chance flood. That presumption appears generally appropriate for open coasts and along many mainland shores of large bays, where the 1-percent-annual-chance SWEL must include some contribution from direct storm surge and thus requires an onshore wind component. However, an assumption of onshore waves coincident with a flood may require detailed justification along the shores of connecting channels, in complex embayments, near inlets, and behind protective islands. Once it is confirmed that sizable waves likely travel onshore at a site during the 1-percent-annual-chance flood, the storm wave condition must be defined for assessments of coastal structure stability, sand dune erosion, wave runup and overtopping, and overland elevations of wave crests.

It is important to recognize that somewhat different descriptions of storm waves (Table D-2) can be appropriate in assessing each distinct flooding effect. This depends mainly on the formulation of an applicable empirical or analytical treatment for each effect. In FIS models and analyses, the different wave descriptions include the following:

- Various wave statistics (e.g., mean wave condition for runup elevations, but an extreme or controlling height for overland waves);
- Various dominant parameters (e.g., incident wave height for overtopping computation, but incident wave period for overland crest elevations); and
- Various specification sites (e.g., deep water for estimating runup elevations, but waves actually reaching a structure in shallow water for most stability or overtopping considerations).

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To proceed with general orientation, the Mapping Partner may develop storm wave conditions from actual wave measurements, from wave hindcasts or numerical computations based on historical effects, and from specific calculations based on assumed storm meteorology. Where possible, the Mapping Partner shall pursue two or all three of these possibilities in estimating wave conditions expected to accompany the 1-percent-annual-chance flood at a study site. Using all available information can improve the level of certainty in estimated storm wave characteristics.

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

**Table D-2. Some Commonly Used Specifications of Irregular Storm Waves**

| SYMBOL | NAME | DESCRIPTION |
|---|---|---|
| **Wave Heights** (water depth must be given) | | |
| $H_s$ | Significant | average over highest one-third of waves |
| $H_c$ | Controlling | defined as (1.6 $H_s$) in NAS (1977) |
| $\overline{H}$ | Mean | average over all waves |
| $H_{mo}$ | zero moment | defined by the variance of water surface, and about equal to $H_s$ in deep water |
| **Wave Periods** (basically invariant with water depth) | | |
| $T_s$ | significant | associated with waves at significant height |
| $T_p$ | peak | represents the maximum in energy spectrum |
| $\overline{T}$ | mean | average over all waves |

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

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

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

Major factors in wave generation are windspeed, wind duration, water depth, and fetch length. Fetch length is he over-water distance toward the wind along which waves arise (USACE, 1994). These factors determine flux of momentum and energy from the atmosphere into waves on the water surface. For some cases, fetch length might be estimated as straight-line distance in the wind direction, but the current ACES guidance pertinent to many partially sheltered coastal sites indicates that a more involved analysis of restricted fetches must be performed for water basins of relatively complex geometry. The effective fetch length is derived as a weighted average of over-water distance with angle from the wind direction. With specified geometry for a restricted fetch, the ACES program carries out computations necessary for the desired estimates of representative wave height and wave period (Leenknecht et al., 1992).

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

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### D.2.2.8 Coastal Structures

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The Mapping Partner shall obtain documentation for each coastal structure possibly providing protection from 1-percent-annual-chance flood. That documentation shall include the following:

- Type and basic layout of structure;
- Dominant site particulars,(e.g., local water depth, structure crest elevation, ice climate);
- Construction materials and present integrity;
- Historical record for structure, including construction date, maintenance plan, responsible party, repairs after storm episodes; and.
- Clear indications of effectiveness or ineffectiveness.

The Mapping Partner shall develop much of this information through office activity, including a careful review of aerial photographs. In some cases of major coastal structures, site inspection would be advisable to confirm preliminary judgments.

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#### D.2.2.9 Historical Floods

While not required as input to any of the FEMA coastal models, local information regarding previous storms and flooding can be very valuable in developing accurate assessments of coastal flood hazards and validation of storm surge models. General descriptions of flooding are useful in determining what areas are subject to flooding and in obtaining an understanding of flooding patterns. More specific information, such as the location of buildings flooded and damaged by wave action, can be used to verify the results of the coastal analyses. Detailed information on pre- and post-storm beach or dune profiles is valuable in checking the results of the erosion assessment.

When quantitative data are available on historical flooding effects, the Mapping Partner shall make a special effort to acquire all recorded water elevations and wave conditions for the vicinity. That information can be used in estimating recurrence intervals for SWELs and for wave action in the event, assisting an appropriate comparison to the 1-percent-annual-chance flood.

Local, county, and state agencies are usually good sources of historical data, especially more recent events. It is becoming common practice for these agencies to record significant flooding with photographs, maps, and/or surveys. Some Federal agencies (e.g., the USACE, USGS, and National Research Council) prepare post-storm reports for more severe storms. Local libraries and historical societies may also be able to provide useful data.

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### D.2.3 Evaluation of Coastal Structures

The purpose of the evaluation is to determine whether each individual coastal structure appears properly designed and maintained in order to provide protection from the 1-percent-annual-chance flood. If a particular structure can be expected to be stable through the 1-percent-annual-chance flood, the structure geometry may figure in all ensuing analyses of wave effects accompanying the flood: coastal erosion, runup and overtopping, and wave crest elevations. Otherwise, the coastal structure is considered to be destroyed during the 1-percent-annual-chance flood and removed from the transect representation before proceeding with analyses of wave effects.

*Criteria for Evaluating Coastal Flood-Protection Structures* presents a technical review and recommends procedural criteria for evaluating coastal flood protection structures in regard to the 1-percent-annual-chance flood (Walton, Ahrens, Truitt, & Dean, 1989). The FEMA "Memorandum on Criteria for Evaluating Coastal Flood Protection Structures for National Flood Insurance Program Purposes" includes an account of the evaluation process (FEMA, 1990). FEMA has adopted that memorandum as the basis for NFIP accreditation of new or proposed coastal structures in reducing effective flood hazard areas and elevations. Ideally, these evaluation criteria could be applied to existing coastal structures, but available information about older structures typically is not sufficient to complete the detailed evaluation. Where complete information is not available for an existing structure, the Mapping Partner shall make an

engineering judgment about its likely stability based on a visual inspection of physical conditions and any historical evidence of storm damage and maintenance.

*Criteria for Evaluating Coastal Flood-Protection Structures* addressed coastal flood protection structures and identified the four primary types according to a functional standpoint: gravity seawalls, pile-supported seawalls, anchored bulkheads, and dikes or levees. The report recommends as a general policy that "FEMA not consider anchored bulkheads for flood-protection credit because of extensive failures of anchored bulkheads during large storms" (Walton et al., 1989, p. 100).

Flood protection structures can have a significant effect on the flood hazard information shown on a FIRM, perhaps directly justifying the removal of sizable areas from the coastal high hazard area. The focus on flood protection structures in the FEMA memorandum cited above should not divert a recognition that similar considerations are appropriate in crediting the protection provided by structures in categories other than those named in the memorandum, and that such credit can be important. In contrast to flood protection, a breakwater primarily may act to limit wave action and a revetment primarily may control shore erosion, but any stable coastal structure can notably affect results of various hazard analyses for the 1-percent-annual-chance flood, and the Mapping Partner shall take these effects into account. The FEMA memorandum places the responsibility on local interests to certify new structures, but the primary consideration in an FIS must be that the structure evaluation yields a correct judgment based on available evidence. This is necessary for accurate hazard assessments, because a structure might decrease flood effects in one area while increasing erosion and wave hazards at adjacent sites. Of course, the greater the potential effects of a coastal structure, the more detailed should be the evaluation process.

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In areas where buildings conforming to V-Zone construction standards are elevated above the wave crest elevation, the Mapping Partner shall model the piles supporting the structure as obstructions in the wave height analysis. The building itself, being elevated, shall not be modeled as an obstruction to wave propagation.

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## D.2.4 Erosion Assessment

Coastal sand dunes usually extend above the 1-percent-annual-chance SWEL, but such barriers to flooding may not be durable because of massive shorefront erosion occurring during a 1-percent-annual-chance flood. Storm-induced erosion will remove or significantly modify most frontal dunes on U.S. coasts. This is particularly true on barrier islands known historically to be susceptible to storm overwash. Therefore, the Mapping Partner shall assess coastal erosion before determining wave elevations and mapping V Zones for the 1-percent-annual-chance flood.

Available procedures for computing erosion show limited precision in documented hindcasts of recorded erosion quantities and have questionable pertinence to the entire range of erosion effects possible on U.S. coasts. Therefore, a rather schematic treatment of expected erosion quantities and geometries has been developed as an appropriate approach for treating erosion in

FISs. The overall rationale and level of detail in these erosion assessment procedures closely parallel the simple and effective NAS methodology for calculating wave action effects associated with storm surges (NAS, 1977).

The procedures described here are empirically valid for treating dune erosion during the 1-percent-annual-chance flood. These procedures are meant to give schematic estimates of eroded profile geometry suitable for FEMA flood study purposes. The simplified estimates are suitable erosion approximations for extreme storms at sandy sites with typical open-coast wave and flood climate. The erosion assessment procedures that follow are intended for application to natural sites where there are no coastal structures such as breakwaters, groins, or revetments. Scour in front of certified structures can account for eroded sand quantities and an adjustment of the shore profile.

Quantitative considerations here are based on measured sand erosion accompanying extreme floods from hurricanes or extratropical storms on the U.S. Atlantic and Gulf coasts (FEMA, November 1988). For the study site, the Mapping Partner may use storm meteorology along with associated flood and wave characteristics to assess whether such open-coast effects can be typical of anticipated local erosion for the 1-percent-annual-chance flood. Of course, the Mapping Partner shall examine any local historical evidence on storm erosion in deciding applicability of the procedures below.

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### D.2.4.1 Basic Erosion Considerations

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The primary factor controlling the basic type of dune erosion is the pre-storm cross section lying above the 1-percent-annual-chance SWEL (frontal dune reservoir). The Mapping Partner shall determine this area to assess the stability of the dune as a barrier. If the elevated dune cross-sectional area is very large, erosion will result in retreat of the seaward duneface with the dune remnant remaining as a surge and wave barrier. On the other hand, if the dune cross-sectional area is relatively small, erosion will remove the pre-storm dune leaving a low, gently sloping profile. Different treatments for erosion are required for these two distinct situations because no available model of dune erosion suffices for the entire range of coastal situations.

Figure D-3 introduces terminology for two representative dune types. A frontal dune is a ridge or mound of unconsolidated sandy soil, extending continuously alongshore landward of the sand beach. The dune is defined by relatively steep slopes abutting markedly flatter and lower regions on each side. For example, a barrier island dune has inland flats on the landward side, and the beach or back beach berm on the seaward side. The dune toe is a crucial feature and can be located as the junction between gentle slope seaward and a slope of 1:10 or steeper marking the front duneface. The rear shoulder, as shown on the mound-type dune in Figure D-3, is defined by the upper limit of the steep slope on the dune's landward side.

The rear shoulder of mound-type dunes corresponds to the peak of ridge-type dunes. Once erosion reaches those points, the remainder of the dune offers greatly lessened resistance and is highly susceptible to rapid and complete removal during a storm. Figure D-3 shows the location of the "frontal dune reservoir," above 1-percent-annual-chance SWEL and seaward of the dune

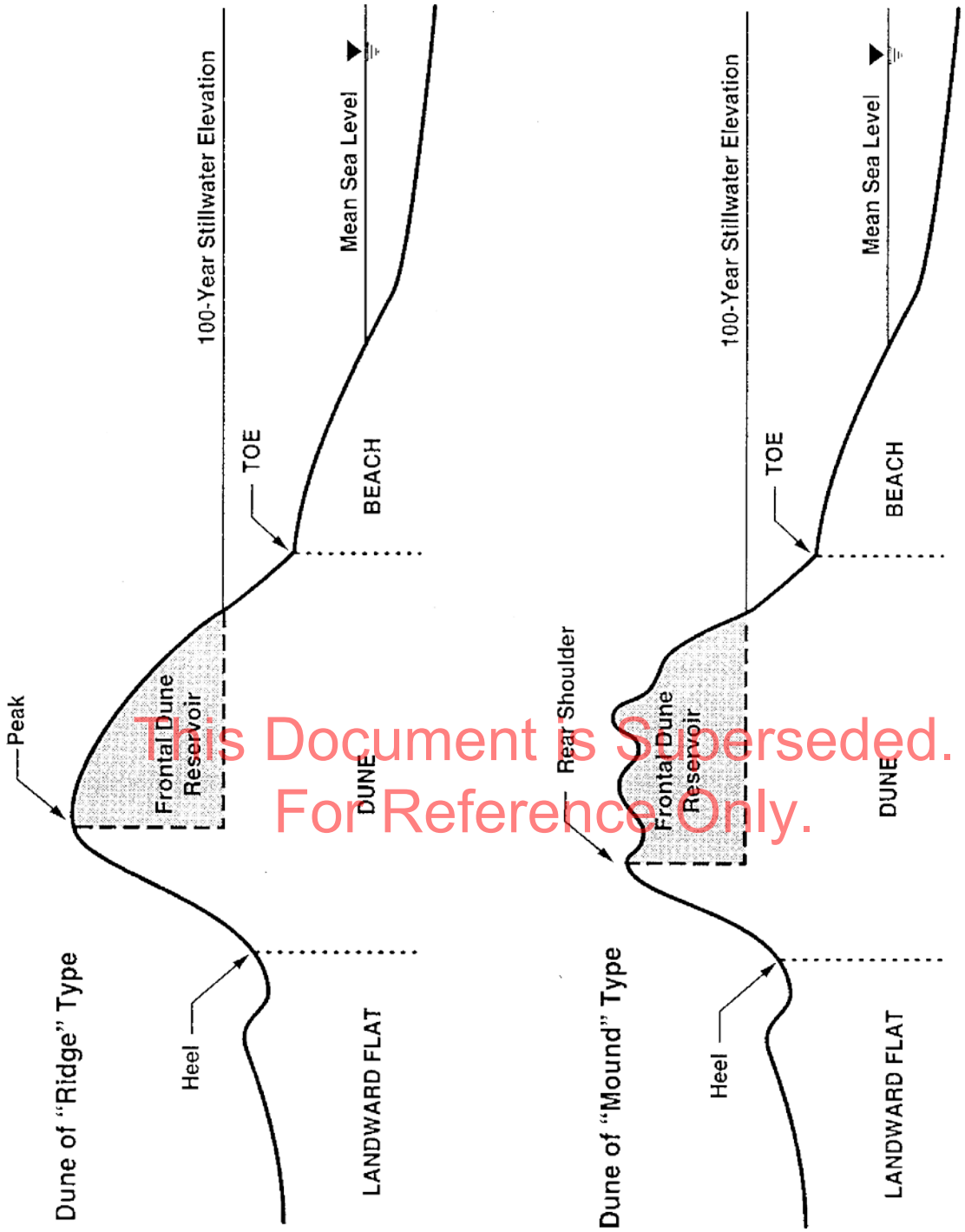


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**Figure D-3. Dune Features and Present Terminology**

peak or rear shoulder. The amount of frontal dune reservoir determines dune integrity under storm-induced erosion.

To prevent dune removal during the 1-percent-annual-chance storm, the frontal dune reservoir must typically have a cross-sectional area of at least 540 square feet (or 20 cubic yards volume per foot along the shore) (FEMA, September 1986; FEMA, November 1988). For more massive dunes, erosion will result in duneface retreat, with an escarpment formed on the seaward side of the remaining dune. To compute the eroded profile in such cases, FEMA has adopted a simplified version of the dune retreat model developed by Delft Hydraulics Laboratory of the Netherlands. This treatment is also appropriate in cases with sandy bluffs or headlands extending above the 1-percent-annual-chance SWEL. The simplified treatment of duneface retreat is described in Subsection D.2.4.3.

If a dune has a frontal dune reservoir less than 540 square feet, storm-induced erosion can be expected to obliterate the existing dune with sand transported both landward and seaward. The Mapping Partner shall estimate the eroded profile using procedures presented in Subsection D.2.4.2. Those procedures provide a realistic eroded profile across the original dune, but do not determine detailed sand redistribution by dune erosion, overwash, and breaching.

Quantitative treatment of overwash processes is not feasible at present (Birkemeier, Kraus, Scheffner, & Knowles, June 1987), so the frontal dune is simply removed.

The initial decision in treating erosion as duneface retreat or as dune removal is based entirely on the size of the frontal dune reservoir. For coastal profiles more complicated than those in Figure D-3, the Mapping Partner shall use judgment to separate the sand reservoir expected to be effective in resisting dune removal from the landward portion of the pre-storm dune. The Mapping Partner shall complete the erosion assessment for the shoreline conditions representative of either the summertime shore profile for hurricane effects or the wintertime shore profile for Northeaster storm effects, whichever is the appropriate and predominant source of coastal flooding that has been selected for use in the coastal hydraulic analyses and erosion assessment.

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Figure D-4 presents a complete flowchart of necessary erosion considerations, outlining the major alternatives of duneface retreat and dune removal. Figure D-5 provides schematic sketches of the different geometries of dune erosion arising in coastal flood hazard assessments.

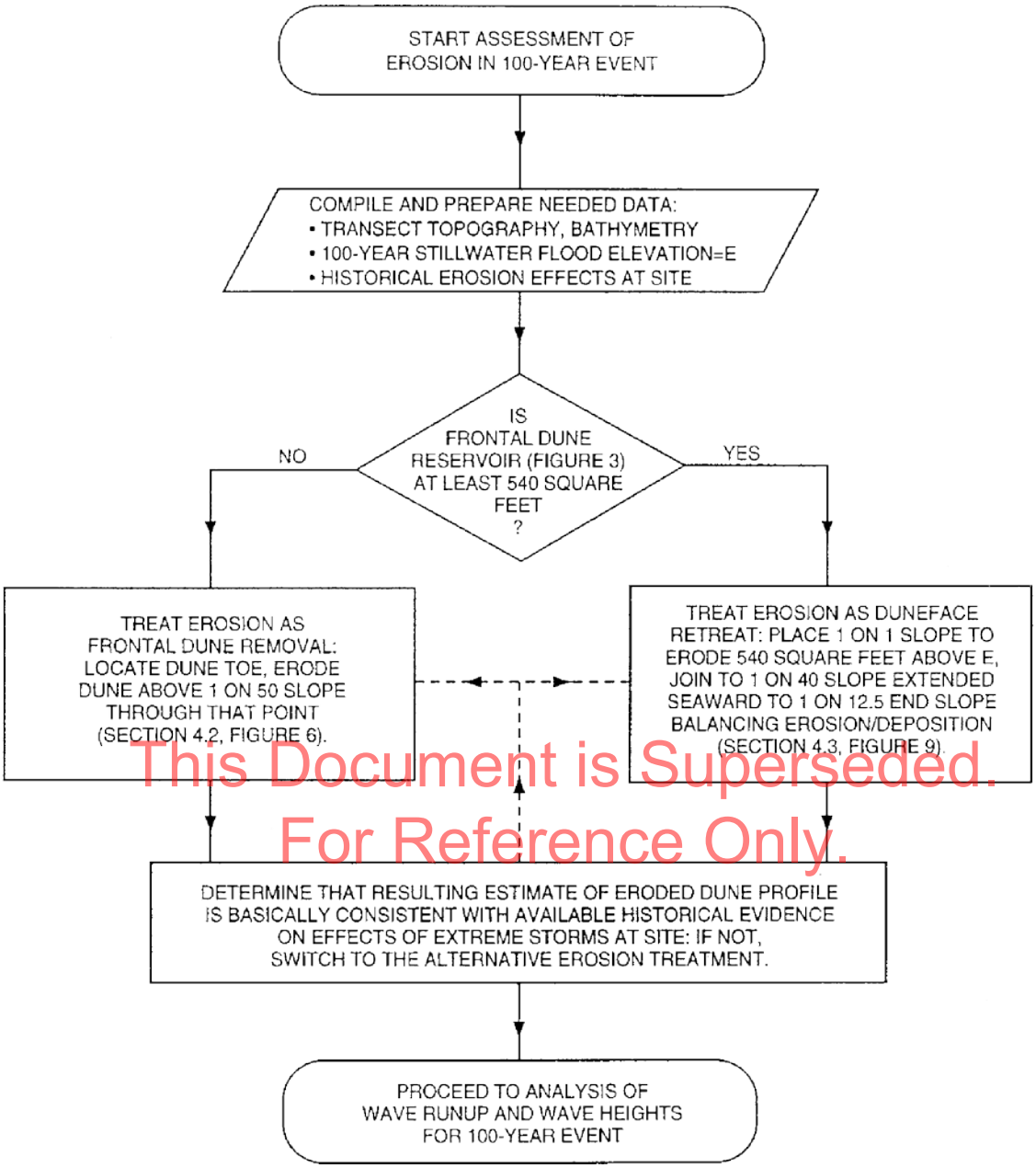


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**Figure D-4. Flowchart of Erosion Assessment for a Coastal Flood Insurance Study**

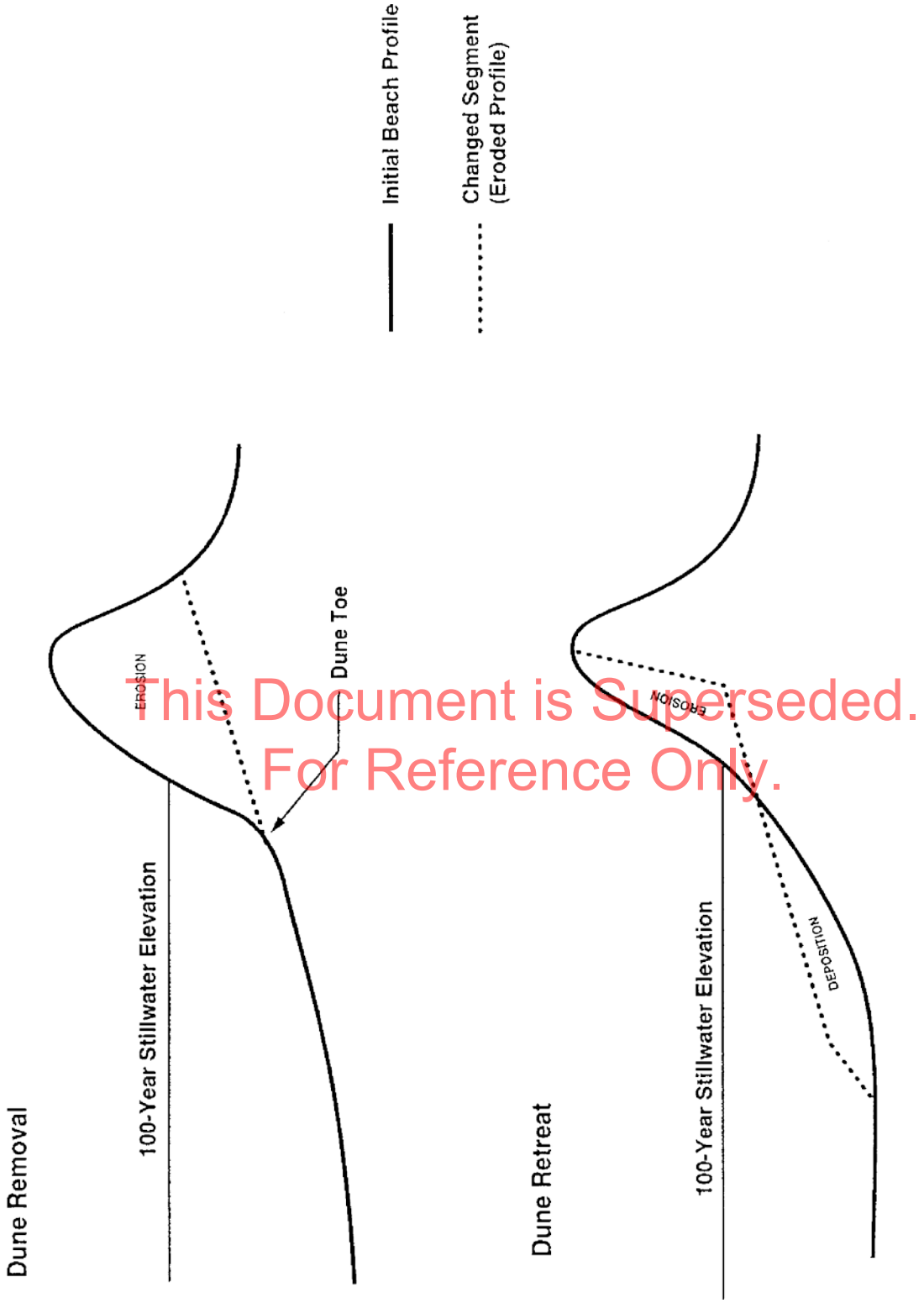


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**Figure D-5. Schematic Cases of Eroded Dune Geometries with Planar Slopes**

One additional factor complicating erosion assessment is the dissipative effect of wide sand beaches that shelter dunes from the full storm impact and retard retreat or removal. If the existing slope between mean level and the 1-percent-annual-chance SWEL is 1:50 or gentler, overestimation of erosion is possible during the 1-percent-annual-chance flood; therefore, the Mapping Partner shall examine this carefully. This effect and other variables, such as sand size, dune vegetation, and actual storm characteristics at a specific site, make thorough comparison of estimated erosion to documented historical effects in extreme storms necessary.

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### D.2.4.2 Treatment of Dune Removal

Determining the dune reservoir requires assessing the profile area located above the 1-percent-annual-chance flood level and seaward of the crest of the primary dune (see Figure D-3). Where the frontal dune reservoir is less than 540 square feet, construction of the eroded profile is extremely simple: dune removal is effected by means of a seaward-dipping slope of 1:50 running through the dune toe. The eroded profile is taken to be that slope across the pre-storm dune, simply spliced onto the flanking segments of a given transect. This gives a gentle ramp across the extended storm surf zone adequate as a first approximation to the profile existing at the storm's peak. This treatment simply removes the major vertical projection of the frontal dune from the transect.

Construction of an eroded profile focuses on the usually distinct feature termed the dune toe. The dune toe is taken to be the junction between the relatively steep slope of the front duneface and the notably flatter seaward region of the beach or the backbeach berm (including any minor foredunes). If a clear slope break is not apparent on a given coastal transect, its location should be taken at the typical elevation of definite dune toes on nearby transects within the study region. The alternative is to set the dune toe at the 10-percent-annual-chance SWEL in the vicinity: that appears to be a generally adequate approximation along the Atlantic and Gulf coasts. In every case, the dune toe must be taken at an elevation above that of any beach berms on local shores.

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Figures D-6, D-7, and D-8 display examples of this treatment for a removed dune. These simple constructions give appropriate estimates for the limits of high ground removed during the 1-percent-annual-chance flood, but cannot provide accurate representations of eroded profiles because of the complicated processes of dune failure. One example of overly simplified results is that deeper scour appears to occur where the frontal dune reservoir is relatively large.

The present viewpoint is consistent with this basic description of storm-induced erosion: greater erosion occurs where the pre-storm barrier provides more resistance; that is, has a relatively large cross section but still is removed during the 1-percent-annual-chance flood. Net shore erosion appears to be maximum for situations where the dune barrier apparently just failed, and the eroded cross section can be much greater than in cases of duneface retreat. A slight opening to landward flow as an eroded dune becomes an overwash channel can result in much deeper scour than in cases of duneface retreat, where most shore erosion is above the SWEL as duneface sand is continuously deposited in shallow water during the storm.

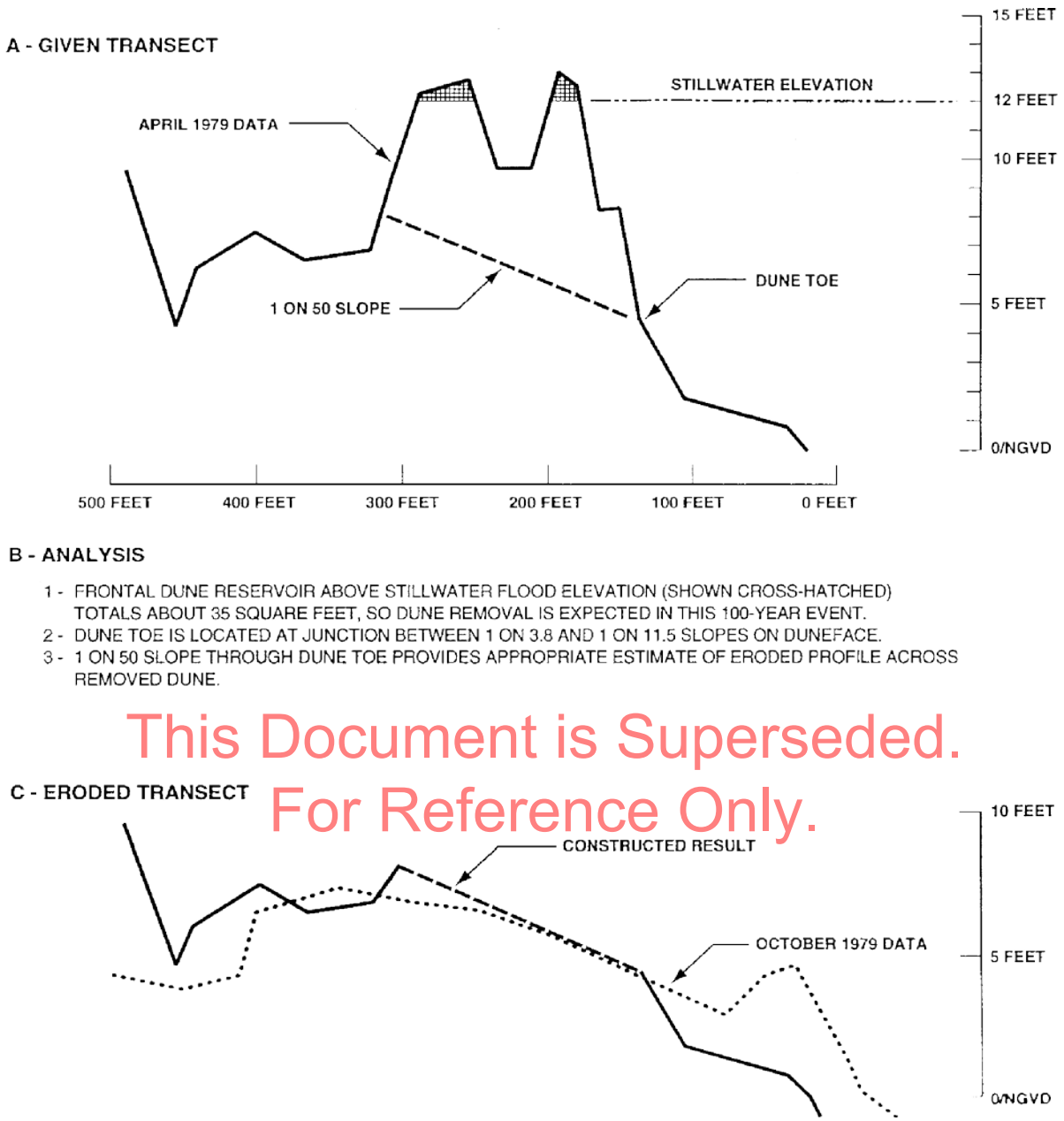


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**Figure D-6. Quantitative Example of Dune Removal Treatment for Alabama Profile Eroded by 1979 Hurricane Frederic. Situation Is Profile B-35 in Baldwin County, Alabama**

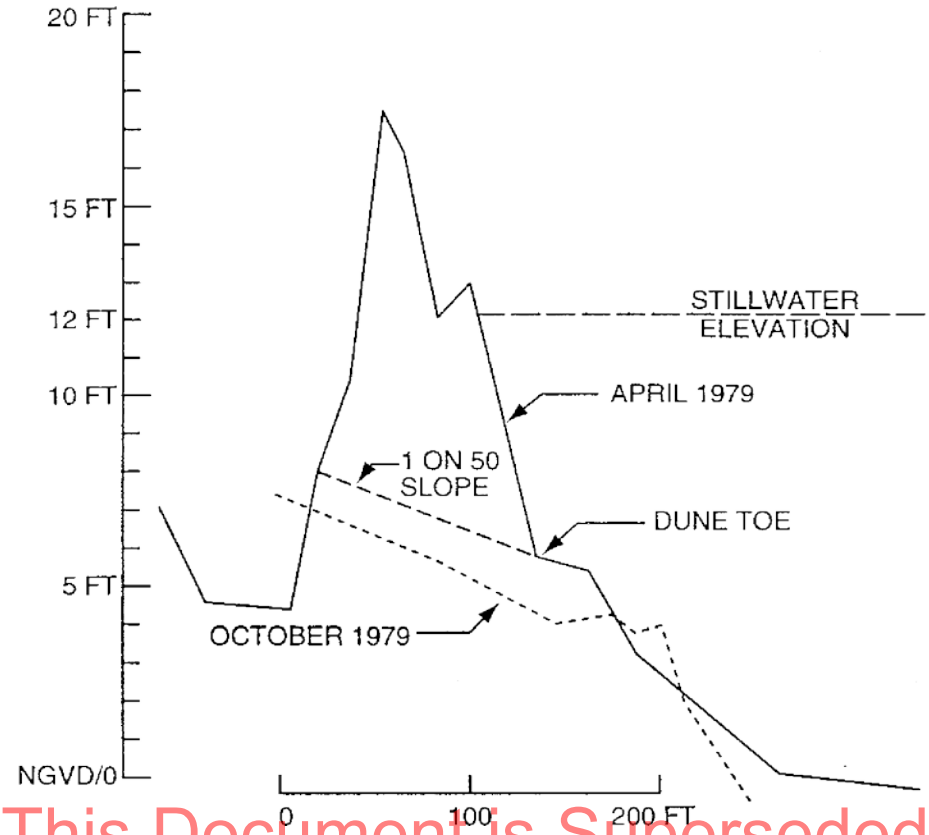


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**Figure D-7. Case of Relatively Large Dune Removed by 1979 Hurricane Frederic in Baldwin County, Alabama**

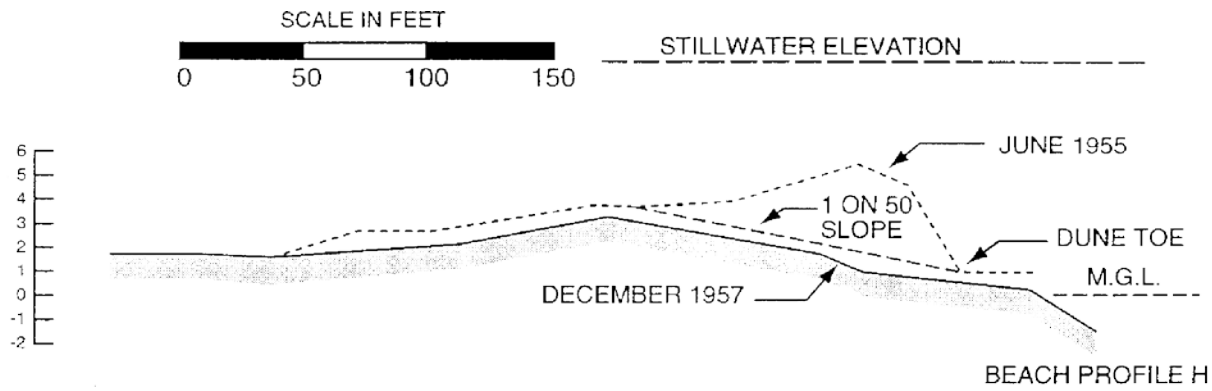


**Figure D-8. Erosion of Relatively Low Profile by 1957 Hurricane Audrey in Cameron Parish, Louisiana**

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### D.2.4.3 Treatment of Duneface Retreat

The procedure described here yields an eroded profile for duneface retreat in the 1-percent-annual-chance flood, for cases where the frontal dune reservoir is at least 540 square feet. During such retreat, the frontal dune barrier remains basically intact and eroded sand is transported in the seaward direction. The post-storm profile provides a balance between sand eroded from the duneface and sand deposited at lower elevations seaward of the dune.

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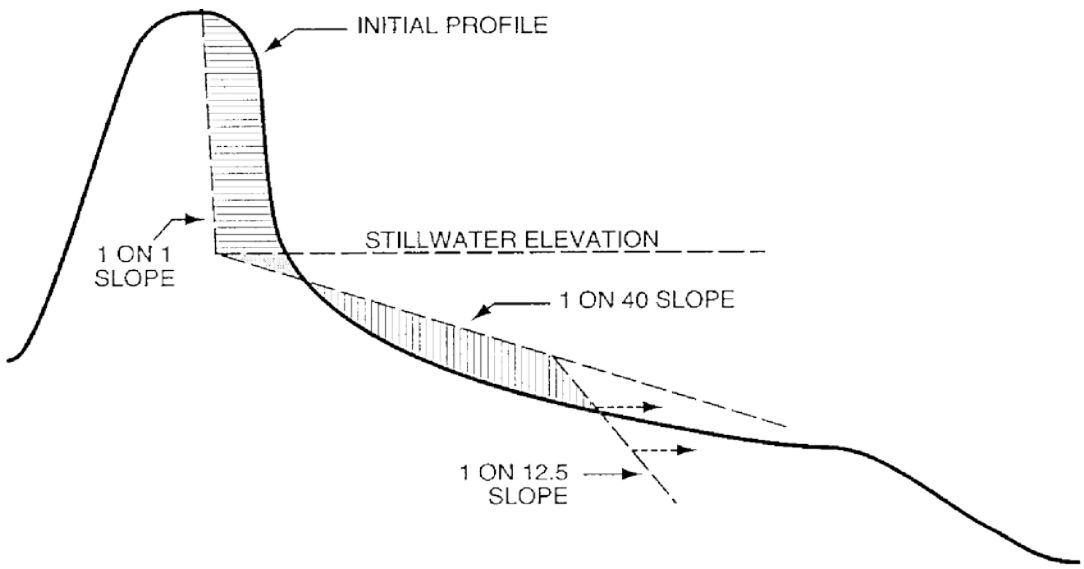
The following procedure for constructing the eroded profile constitutes a simplification of the dune retreat model developed by Delft Hydraulics Laboratory (DHL) of the Netherlands (Vellinga, 1986). Erosion above 1-percent-annual-chance SWEL is fixed at 540 square feet, to guarantee an appropriate amount for the U.S. Atlantic and Gulf coasts (FEMA, 1986 and November 1988). (In the DHL model, erosion is determined as the variable depending on specified storm and site conditions.)

Figure D-9 summarizes the simple procedure adopted to treat cases of duneface retreat. The eroded profile consists of three planar slopes: uppermost is a retreated duneface slope of 1:1, joining an extensive middle slope of 1:40, which is terminated by a brief segment with a slope of 1:12.5 at the limit to storm deposition. Upper dune erosion is specified to be 540 square feet above the 1-percent-annual-chance SWEL and in front of the 1:1 slope. Geometrical construction balances the nearshore deposition with the total dune erosion of somewhat more than 540 square feet by an appropriate seaward extension of the 1:40 slope. The resulting eroded profile is spliced onto the unchanged landward and seaward portions of the pre-storm profile. This procedure gives a complete profile suitable for use with the Wave Runup Model in assessing an appropriate flood elevation on the dune remnant.




PROCEDURE:

1 - CONSTRUCT RETREATED DUNEFACE WITH 540 $FT^2$ EROSION [ ] ABOVE 100-YEAR STILLWATER ELEVATION AND SEAWARD OF 1 ON 1 SLOPE.

2 - DETERMINE ADDITIONAL DUNE EROSION QUANTITY, SHOWN DOTTED, IN WEDGE BETWEEN STILLWATER ELEVATION, 1 ON 40 SLOPE, AND INITIAL PROFILE.

3 - BALANCE TOTAL DUNE EROSION WITH POSTULATED DEPOSITION [ ] BY APPROPRIATE PLACEMENT OF 1 ON 12.5 SLOPE AS LIMIT TO DEPOSITION.

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**Figure D-9. Procedure Giving Eroded Profile in Cases of Duneface Retreat, and Simplification of Dune Retreat Model Developed by Delft Hydraulics Laboratory of the Netherlands)**

Figure D-10 presents an example of duneface retreat according to the present procedure. This simple construction of a retreated dune profile gives appropriate eroded slopes important to the wave runup analysis of the remaining barrier. For this example, estimated erosion and deposition do not match well with those recorded, because there is a net sand loss shown on this profile and the event appears somewhat less extreme than a 1-percent-annual-chance flood (judging from reported characteristics of Hurricane Eloise). Where historical data on duneface retreat are available for comparison, agreement of estimated erosion slopes with those recorded should be considered of primary importance in verifying the present treatment. Actual quantities of dune erosion are subject to large variations in natural situations, and this procedure presumes a generally representative value for 1-percent-annual-chance flood conditions.

The Mapping Partner shall apply the basic procedure illustrated in Figure D-9 in estimating erosion of high open-coast headlands or bluffs of sandy material.

This modification to the DHL model eliminates potential problems associated with computation sensitivity to storm wave height and with uncertain capabilities for situations dissimilar to the Netherlands coast (Birkemeier et al., 1987; FEMA, November 1988). The other modifications of the model and treatment of duneface retreat have been implemented in an attempt to simplify the treatment by ignoring the variation of sand size and approximating the planar slope to the curved segment of the DHL post-storm profile.

In such cases, parallel retreat of the existing face slope should be presumed, rather than using the typical 1:1 slope for the escarpment on an eroded sand dune, because that existing slope reflects actual consolidation properties of the headland or bluff material.

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### D.2.4.4 Finalizing Erosion Assessment

Based on measured erosion along the Atlantic and Gulf coasts, the demarcation between duneface retreat and dune removal in a 1-percent-annual-chance flood has been set at a frontal dune reservoir of 540 square feet (FEMA, 1986 and November 1988). This quantitative criterion might appear too precisely stated, in view of potential inaccuracies in available dune topography, possible complications in delineating the effective frontal dune reservoir, and documented variability of dune erosion during extreme storms. In fact, the likelihood of duneface retreat or dune removal cannot be assessed with full certainty, so that validating the present erosion assessment by means of available evidence for a specific site is advisable.

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At many sites, some historical evidence may be available regarding the extent of flooding, erosion, and damage in an extreme event comparable to the local 1-percent-annual-chance flood. Then the erosion treatment giving results more consistent with historical records must be selected as appropriate. That choice may be relatively clear-cut, given potential differences in expected erosion and inland flood penetration for duneface retreat versus dune removal. Where available historical evidence is not definitive, the decision between retreat and removal on a given transect should be based solely on size of the frontal dune reservoir. Present procedures for erosion assessment are highly simplified, but provide an unbiased estimation and a level of detail appropriate to coastal FISs.

[February 2002]

### D.2.4.5 Wave Overtopping for Cases of Duneface Retreat

Where the erosion assessment indicates duneface retreat, an eroded dune remnant persists as an appreciable barrier to the 1-percent-annual-chance flood. However, storm wave action can result in occasional extreme runups overtopping that barrier, yielding floodwaters running off or ponding landward of the dune. DHL has determined the mean overtopping rate with storm waves incident on a typical duneface retreat geometry determined by the DHL (1983) to be

$$\overline{Q} = 5.26 \exp\left[-0.253\, F\right] . \qquad (1)$$

Here the overtopping rate $\overline{Q}$1 has units of cubic feet per second per foot alongshore (cfs/ft), and $F$ is maximum height (in feet) of the dune remnant above SWEL.

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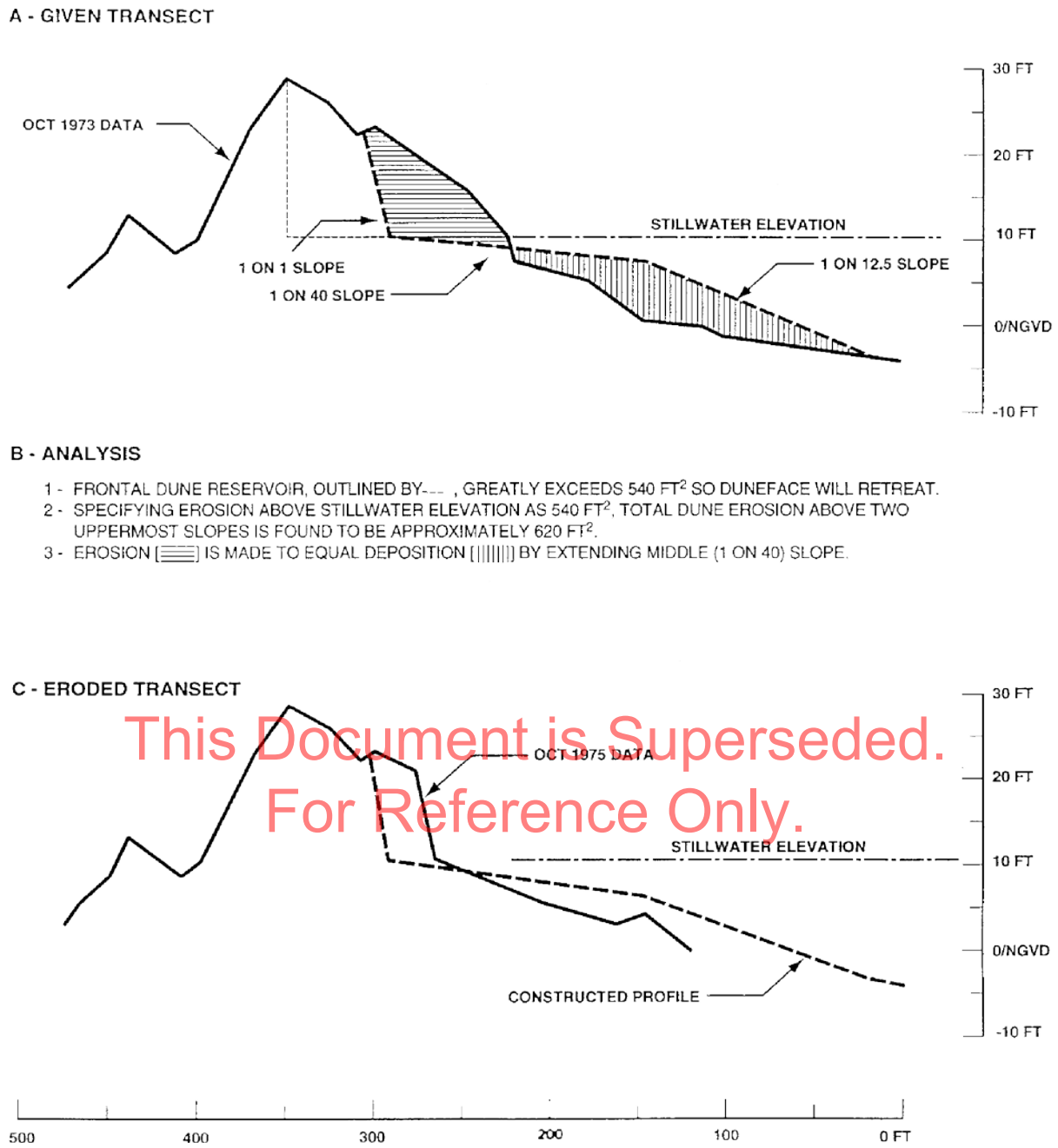


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**Figure D-10. Example of Duneface Retreat Treated by Simplified version of D.H.L. model, with erosion Above SWEL Fixed at 540 Square Feet. Situation Is Profile R-105 in Walton County, Florida, Surveyed Before and After 1975 Hurricane Eloise**

This result was measured in DHL tests scaled to reproduce a specific extratropical storm on the Dutch seacoast, with a significant deep-water wave height of 25 feet and a peak wave period of 12 seconds. Those wave conditions seem roughly representative for the 1-percent-annual-chance flood along U.S. seacoasts, although expected wave characteristics will differ between hurricanes and extratropical storms at various sites. Recorded rates of overtopping can show sizable departures from the expected mean even with steady flood conditions (Goda, 1985; Owen, 1980).

Despite uncertainties about actual overtopping rates for a dune remnant, the equation gives a useful basis for outlining expected effects. The order of magnitude for severe overtopping may be taken as 1 cfs/ft, past allowable thresholds for structural integrity with bare soil behind steep barriers exposed to storm waves (Goda, 1985). From Equation 1, $\overline{Q}2$ of approximately 1 cfs/ft corresponds to $F$ of approximately 7 feet, so retreated remnants with less relief above the 1-percent-annual-chance SWEL certainly require consideration of possible flood hazards landward of the dune. Appropriate treatments for ponding or runoff behind barriers are outlined in Subsection D.2.6.

[February 2002]

## D.2.5 Wave Runup, Setup, and Overtopping

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Wave runup is the uprush of water from wave action on a shore barrier intercepting stillwater level. The water wedge generally thins and slows during its excursion up the barrier, as residual forward momentum in wave motion near the shore is fully dissipated or reflected. The notable characteristic of this process for present purposes is the wave runup elevation, the vertical height above stillwater level ultimately attained by the extremity of uprushing water. Wave runup at a shore barrier can provide flood hazards above and beyond those from stillwater inundation and incident wave geometry, as illustrated in Figure D-11.

Two additional phenomena, wave setup and wave overtopping, may require explicit consideration for adequate treatment of the coastal flood hazards linked to wave runup. Wave setup generates a mean water surface elevated above the SWFL, caused by accumulation of water against a barrier exposed to wave heights attenuating in shallow water. Wave overtopping consists of any wave-induced flow passing over the barrier crest, so that flood water may exhibit wave, sheet flow, or ponding characteristics over an inland area. These phenomena and their quantitative evaluation will be addressed later in this Appendix.

The extent of runup can vary greatly from wave to wave in storm conditions, so that a wide distribution of wave runup elevations provides the precise description for a specific situation. Current policy for the NFIP is that the mean runup elevation (rather than some occasional extreme) for a situation is appropriate in mapping coastal hazards of the 1-percent-annual-chance flood.

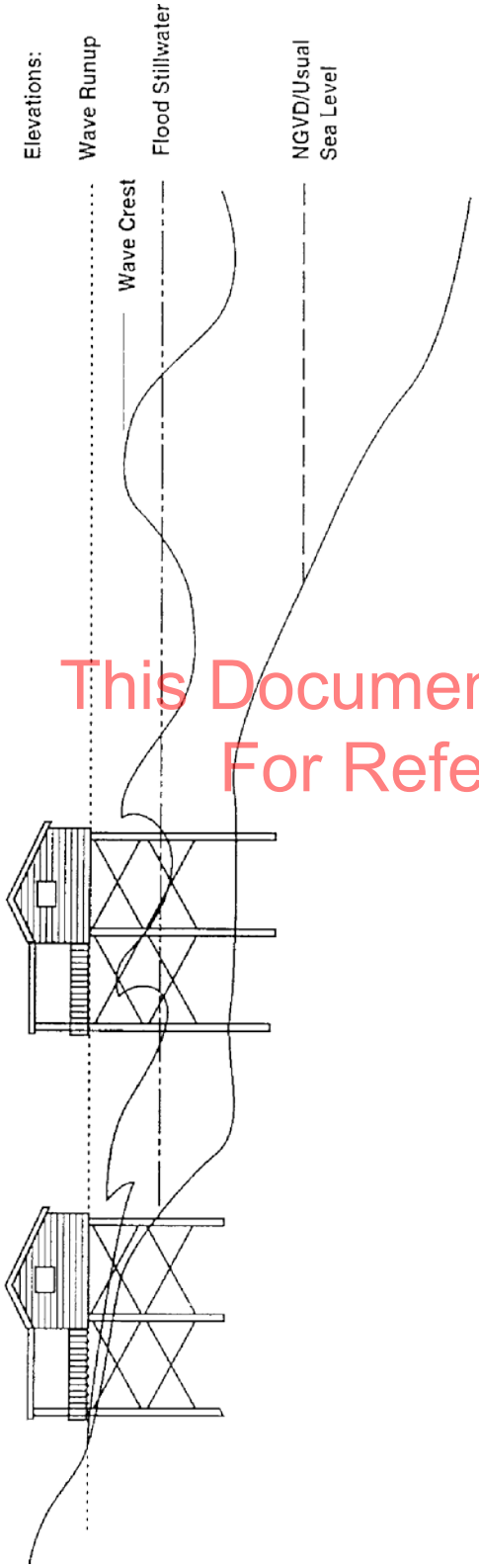


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**Figure D-11. Schematic Illustration of Wave Effects Extending Above and Landward of Stillwater Intercept on Transect**

[February 2002]

### D.2.5.1 Wave Runup Model Description

The current version of the FEMA Wave Runup Model, RUNUP 2.0, may be run either on a minicomputer (e.g., DEC VAX 11/750) or on an IBM-compatible personal computer (PC or PC/AT). Given the flood level, shore profile and roughness, and incident wave condition described in deep water, the program computes by iteration a wave runup elevation fully consistent with the most detailed guidance available (Stoa, 1978). This determination includes an analysis separating the profile into an approach segment next to the steeper shore barrier, and interpolation between runup guidance for simple configurations bracketing the specified situation.

Some additional description of the workings of the Wave Runup Model can assist informed preparation of input and interpretation of output. The incorporated guidance gives runup elevation as a function of wave condition and barrier slope, for eight basic shore configurations distinguished by water depth at the barrier toe, along with the approach geometry. Where those basic geometries do not appropriately match the specified profile, reliance is placed on the composite slope method (Saville, 1958); this assumes the input shore profile (composite slope) is equivalent to a hypothetical uniform slope, as shown in Figure D-12. The runup elevations are derived from laboratory measurements in uniform wave action, rather than the irregular storm waves usually accompanying a flood event. Runup guidance for uniform waves, however, also pertains to the mean runup elevation from irregular wave action with identical mean wave height and mean wave period. Figure D-13 presents an overview of the basic computation procedure within RUNUP 2.0.

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Basic empirical guidance incorporated within this computer model generally does not extend to vertical or nearly vertical flood barriers. For such configurations, RUNUP 2.0 usually will provide a runup elevation, but the result may be misleading because reliance on the composite-slope method can yield an underestimate of actual wave runup with the abrupt barrier. Where a vertical wall exists on a transect, the Mapping Partner shall develop a runup estimate using specific guidance in Figure D-14, taken from the *Shore Protection Manual* (USACE, 1984). As within RUNUP 2.0, these empirical results for uniform waves should be utilized by specifying mean wave height and mean wave period for entry, and taking the indicated runup as a mean value in storm wave action. Shore configurations with a vertical wall are also addressed separately in Subsection D.2.5.7.

[February 2002]

### D.2.5.2 Wave Runup Model Input Preparation

The input to the Wave Runup Model is done by transects. As specified in Subsection D. 2.2, the Mapping Partner shall locate transects along the shoreline. Because the runup results are very sensitive to shore slope or steepness, it is important to have at least one transect for each distinct type of shore geometry. Often, areas with similar shore slopes are located throughout a community, and the results of one transect can be applied to all the areas that are similar. This is

especially typical of New England communities with rocky bluffs. When the Wave Runup Model is being applied to dune remnants where eroded slopes are fairly uniform, transect location is governed by the upland land-cover characteristics, which are major considerations in

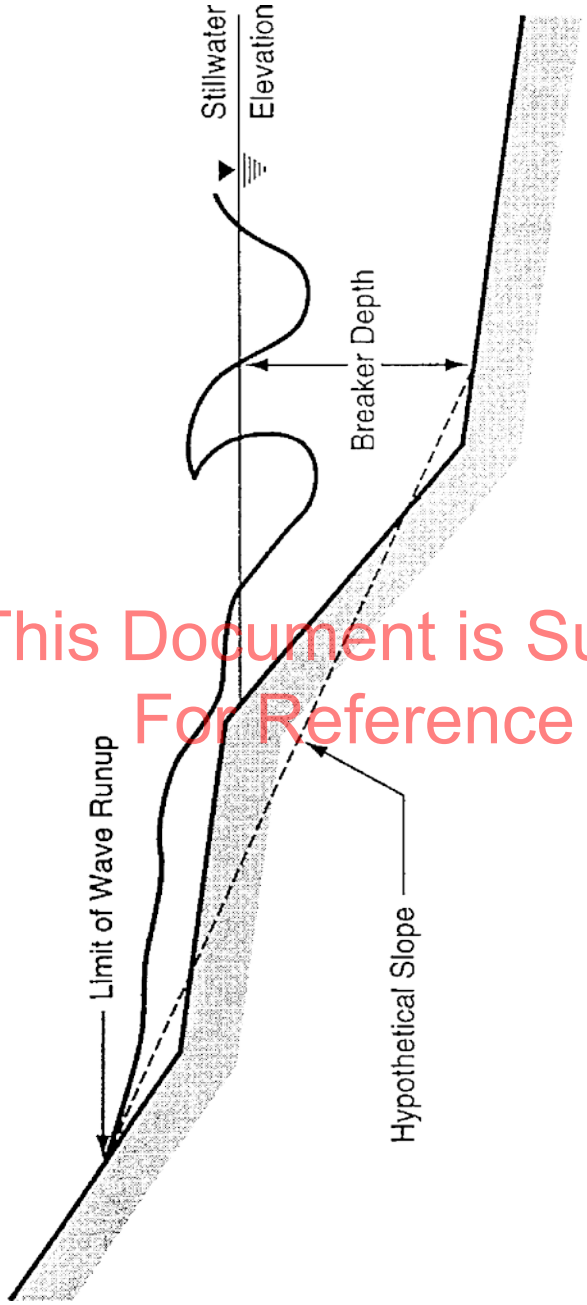


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**Figure D-12. Hypothetical Slope for Determining Wave Runup on Composite Profiles**

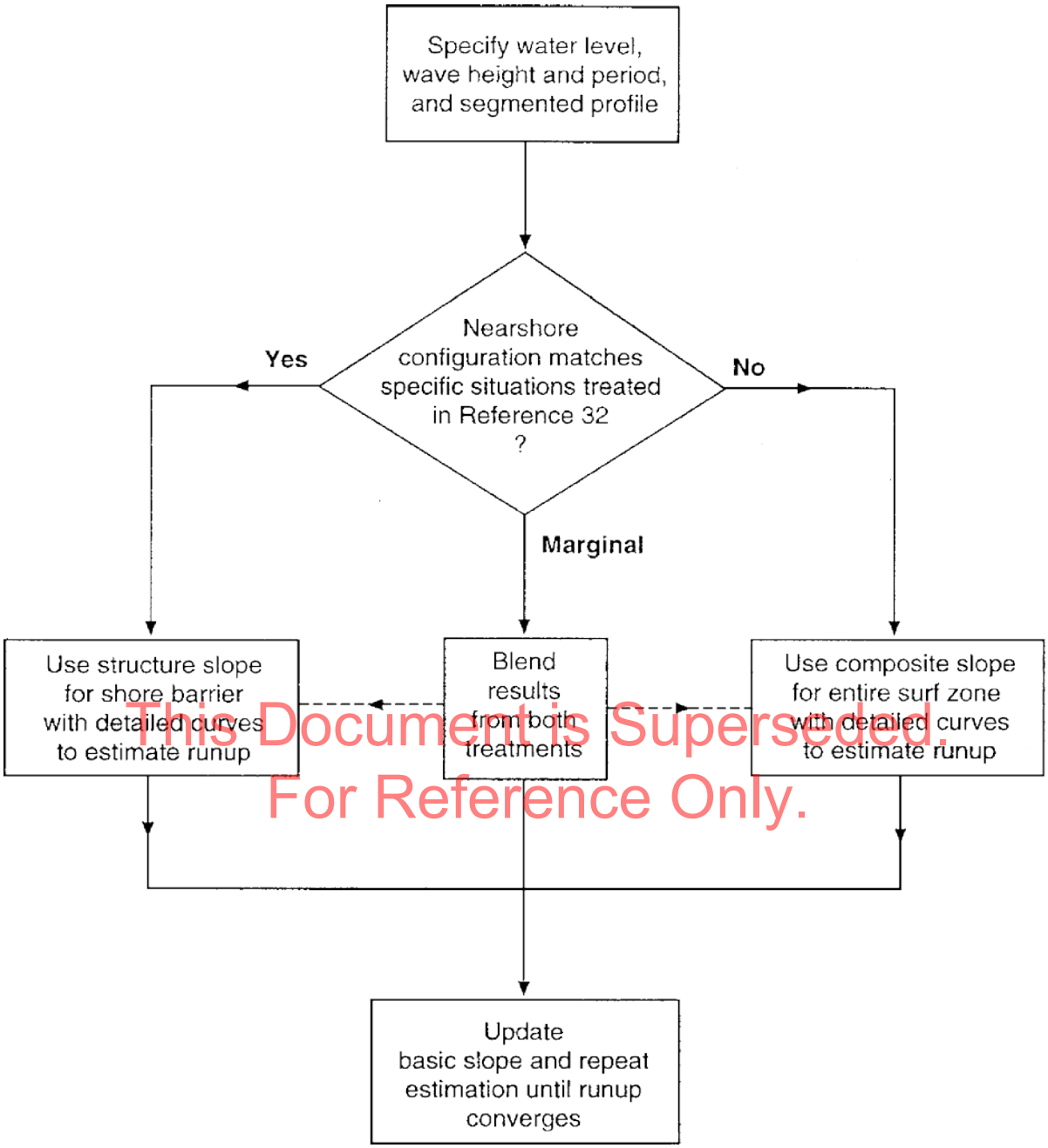


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**Figure D-13. Overview of Computation Procedure Implemented in Modified FEMA Wave Runup Model**

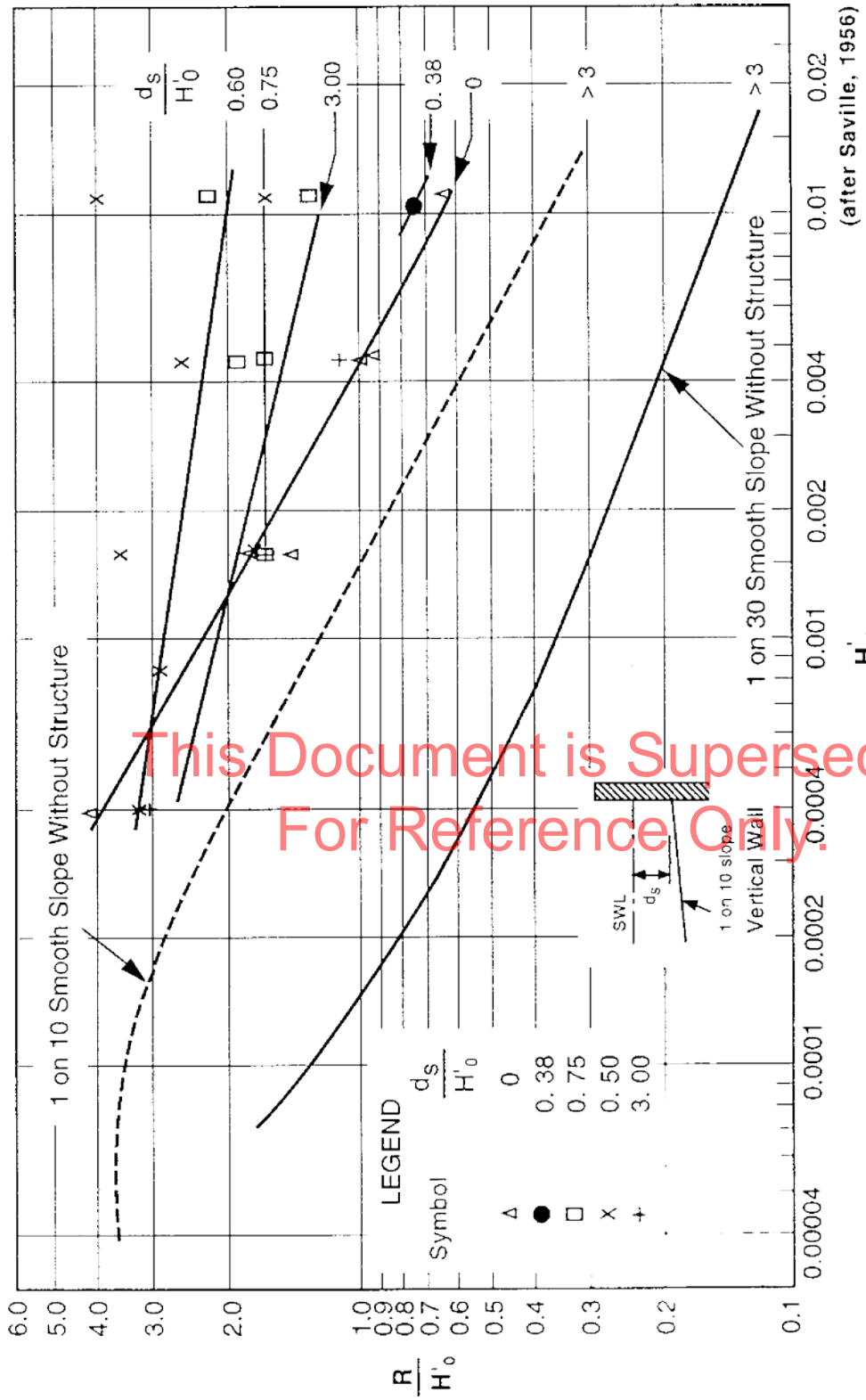


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**Figure D-14. Wave Runup Guidance from Vertical Wall, From *Shore Protection Manual* (USACE, 1984)**

in the WHAFIS model.

The ground profile for the transect is plotted from the topography and bathymetry after the data have been referenced to the National Geodetic Vertical Datum (NGVD). The profile must extend from an elevation below the breaker depth to an elevation above the limit of runup or to the maximum ground elevation. An adequate vertical extent for the transect description will usually be 1.5 times the wave height above and below the SWEL. If the landward profile does not extend above the computed runup (30 feet NGVD is commonly a maximum), it will be assumed that the last positive slope segment continues indefinitely. This is very common with low barriers, so the Mapping Partner shall select the last slope carefully so it is representative. To complete the description, each slope segment of the profile will need a roughness coefficient, with some common values presented in Table D-3. The roughness coefficient must be between zero (maximum roughness) and one (hydraulically smooth), and values for slope segments above the SWFL control the estimated runup. The roughness coefficient *(r)* is used as a multiplier for runup magnitude *(R)* defined on a smooth barrier to estimate wave runup with a rough barrier.

**Table D-3. Values for Roughness Coefficient in Wave Runup Computations**

| ROUGHNESS COEFFICIENT | DESCRIPTION OF BARRIER SURFACE |
|---|---|
| 1.00 | Sand; smooth rock, concrete, asphalt, wood, fiberglass |
| 0.95 | Tightly set paving blocks with little relief |
| 0.90 | Turf, closely set stones, slabs, blocks |
| 0.85 | Paving blocks with sizable permeability or relief |
| 0.80 | Steps; one stone layer over impermeable base; stones set in cement |
| 0.70 | Coarse gravel; gabions filled with stone |
| 0.65 | Rounded stones, or stones over impermeable base |
| 0.60 | Randomly placed stones, two thick on permeable base; common rip-rap installations |
| 0.50 | Cast-concrete armor units: cubes, dolos, quadripods, tetrapods, tribars, etc. |

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Transects are approximated by the minimum adequate number of linear segments, up to a limit of 20. Segments may be horizontal, or higher at the landward end; portions with opposite inclination should be represented as horizontal when developing the transect approximation. Using many linear segments to represent a transect can be wasted effort, because the Wave Runup Model may combine adjacent segments in defining the appropriate approach and barrier extents. With the runup computation procedure, the Mapping Partner shall apply engineering judgment to transect representation to assist in obtaining the most valid estimate of wave runup elevation.

The input transect must reflect wave-induced modifications expected during the 1-percent-annual-chance event, including erosion on sandy shores with dunes. The Mapping Partner shall represent only coastal structures expected to remain intact throughout the 1-percent-annual-chance event on a specific transect. Besides the transect specification, other required input data for the Wave Runup Model are the 1-percent-annual-chance SWEL and the incident mean wave condition described in deep water. The specified SWEL should exclude any contributions from

wind-wave effects. If available elevations include wave setup, the Mapping Partner shall remove that component before using this model so that calculated runup elevations do not indicate a doubled wave setup. Basic empirical guidance relates runup at a barrier to the water level in the absence of wave action and thus includes the wave setup component.

The mean wave condition to be specified for valid results with the Wave Runup Model may be derived from other common wave descriptions by simple relationships. Wave heights in deep water generally conform to a Rayleigh probability distribution, so that mean wave height equals 0.626 times either the significant height based on the highest one-third of waves or the zero-moment height derived from the wave energy spectrum. No exact correspondence between period measures exists; but, mean wave period usually can be approximated as 0.85 times the significant wave period or the period of peak energy in the wave spectrum.

Table D-4 lists a series of wave height and period combinations, of which one should be fairly suitable for runup computations at fully exposed coastal sites (depending on the local storm climate). These mean wave conditions have wave steepness values typical of U.S. hurricanes or within 30 percent of a fully arisen sea for extratropical storms. Commonly, the Mapping Partner may have some difficulty in specifying a precise wave condition as accompanying the 1-percent-annual-chance flood. In that case, is the Mapping Partner also shall consider wave heights and periods both 5 percent higher and 5 percent lower than that selected (or whatever percentages suit the level of uncertainty) and shall run the model with all nine combinations of those values. The average of computed runup values then provides a suitable estimate for mean runup elevation. A wide range in computed runups signals the need for more detailed analysis of expected wave conditions or for reconsideration of the transect representation.

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**Table D-4. Appropriate Wave Conditions for Runup Computations Pertaining to 1-Percent-Annual-Chance Event in Coastal Flood Insurance Studies**

| MEAN WAVE PERIOD (SECONDS) | MEAN DEEP WATER WAVE HEIGHT (FEET) |
|---|---|
| **HURRICANES** | |
| 8 | 12 |
| 9 | 15.5 |
| 10 | 19 |
| 11 | 23 |
| 12 | 27.5 |
| **EXTRATROPICAL STORMS** | |
| 11 | 18 |
| 12 | 21.5 |
| 13 | 25 |
| 14 | 29 |
| 15 | 33.5 |

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### D.2.5.3 Wave Runup Model Operation

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The input to the FEMA Wave Runup Model consists of several separate lines specifying an individual transect and the hydrodynamic conditions of interest within particular columns. All input information is echoed in an output file, which also includes computed results on wave breaking and wave runup.

The input format is outlined in Table D-5. The first two lines of the input give the Name and Job Description, which must be included for each transect. The next line of input is the Last Slope, which contains the cotangent of the shore profile continuing from the most landward point provided. This is followed by the profile points, which define the nearshore profile in consecutive order from the most seaward point. Each line gives the elevation and station of a profile point and the roughness coefficient for the segment between that point and the following point. The roughness coefficient on the last profile line is for the continuation defined in the Last Slope line. The number of profile points cannot exceed 20. The final input is the series of hydrodynamic conditions of interest. Each line here contains the SWEL along with a mean wave height in deep water and a mean wave period.

**Table D-5. Description of Five Types of Input Lines for Wave Runup Model**

Name Line

This line is required and must be the first input line.

| Columns | Contents |
|---|---|
| 1-2 | Blank |
| 3-28 | Client's Name |
| 29-60 | Blank |
| 61-70 | Engineer's Name |
| 71-80 | Job Number |

Job Description Line

| Columns | Contents |
|---|---|
| 1-2 | Blank |
| 3-76 | Project description or run identification |
| 77-80 | Run Number |

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Last Slope Line

This line is required and defines the slope immediately landward of the profile actually specified in detail.

| Columns | Contents |
|---|---|
| 1-4 | Slope (horizontal over vertical or cotangent) of profile continuation |
| 5-80 | Blank |

Profile Lines

These lines must appear in consecutive order from the most seaward point landward. Each line has the elevation and station of a profile point and the roughness coefficient for the section between that point and the following point. The roughness coefficient on the last profile line is for the continuation defined in the Last Slope Line. The Mapping Partner shall ensure that at least one profile point with a ground elevation greater than the SWEL is specified. The number of Profile Lines cannot exceed 20.

| Columns | Contents |
|---|---|
| 1 | Last point flag. The most landward point on the profile is indicated by a 1. If not the last point, leave blank. |

| | |
|---|---|
| 2 | Blank |
| 3-7 | Elevation with respect to NGVD, in feet |
| 8 | Blank |
| 9-14 | Horizontal distance. It is common to assign the shoreline (elevation 0.0) as Point 0 with seaward distances being negative and landward distances positive. |
| 15 | Blank |

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**Table D-5. Description of Five Types of Input Lines for Wave Runup Model (Cont'd).**

| Columns | Contents |
|---|---|
| 16-20 | Roughness coefficient in decimal form between 0.00 (most rough) and 1.00 (smooth). |
| 21-80 | Blank |

Water Level and Wave Parameter Lines

These lines specify hydrodynamic conditions for runup calculations on each profile. Namely, 1-percent-annual-chance SWEL along with mean wave height and period for deep water. Typically, SWEL remains constant for a given profile, while the selected wave conditions closely bracket that expected to accompany the 1-percent-annual-chance flood. A maximum of 50 of these lines can be input for each profile.

| Columns | Contents |
|---|---|
| 1 | Last line, new transect flag. A 1 indicates the last line for a given transect and notifies that another transect is following. If not the last line, or if the last line of the last transect, leave blank. |
| 2-6 | SWEL with respect to NGVD, in feet. |
| 7 | Blank |
| 8-12 | Deepwater mean wave height, $\overline{H}$3o, in feet, greater than 1 foot |
| 13 | Blank |
| 14-18 | Mean wave period, $\overline{T}$4, in seconds |
| 19-80 | Blank |

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The output as shown in Table D-6 has two parts. The first page is a printout of the transect listed as a numbered set of profile points, cotangents (slopes) of the segments, and the roughness coefficient for each segment. The second page is the output table of computed results for each set of conditions: the values of runup elevation and breaker depth, each with respect to the specified SWEL, along with an identification of the segment numbers giving the seaward limit to wave breaking and the landward limit to mean wave runup.

[February 2002]

### D.2.5.4 Wave Runup Model Output Messages

Several output messages alert the user to specific problems encountered in running the program. All but the last three indicate that the program has stopped execution without completing runup calculations.

- "NEGATIVE RUN PARAMETER, PROGRAM STOPS"

An input value of wave height or wave period is read as negative or zero. Check that the input has been entered in the correct columns.

- "MORE THAN 20 POINTS IN PROFILE, PROGRAM STOPS"

  The program accepts a maximum input of 20 points defining the nearshore profile. This encourages a profile approximation that is not overly detailed, because each transect is to represent an extensive area.

- "**** $H_o/L_o$ LESS THAN 0.002 ****" or
  "**** $H_o/L_o$ GREATER THAN 0.07 ****"

  These limits on wave steepness pertain to the extent of incorporated guidance on breaker location. They should be adequate to include appropriate mean wave conditions for extreme events and also conform to the usual limits in detailed guidance on wave runup elevations.

- "DATA EXCEEDED TABLE"

  An entry into subroutine LOOK of the program is not within the parameter bounds of the data table from which a value is sought.

- "SOLUTION DOES NOT CONVERGE"

  After 10 iterations, the current and previous estimates of runup elevation continue to differ by more than 0.15 foot, and both values are provided in the output table. The calculation is usually oscillating between these two runup estimates when this occurs.

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- "COMPOSITE SLOPE USED BUT WAVE MAY REFLECT, NOT BREAK"

  The output runup elevation relies to some extent on a composite-slope treatment, but the overall slope is steep enough that the specified wave may reflect from the nearshore barrier. Thus, the application of a calculated breaker depth in determining overall slope and runup elevation is questionable.

- "WARNING; COMPOSITE SLOPE USED, BUT INPUT PROFILE DOES NOT EXTEND TO BREAKER DEPTH"

  If the input profile does not extend seaward of the breaker depth, an incorrect breaker depth may be computed and the associated runup elevation will also be incorrect. The input profile should include bathymetry to 30 or 40 feet in depth.

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### D.2.5.5 Wave Runup in Special Situations

To interpret and apply the calculated results properly, the Mapping Partner shall examine the output of the Wave Runup Model carefully for each situation. One important consideration is that a mean runup elevation below the crest of a given barrier does not necessarily imply the barrier will not occasionally be overtopped by floodwaters; the necessary supplementary examination of wave overtopping is addressed in Subsection D.2.5.7. Other cases may yield

```
CLIENT- FEMA                        ** WAVE RUNUP-VERSION 2.0  ** ENGINEERED BY DAB       JOB 1
PROJECT-Runup calculations on Eroded Transect                                   RUN 1    PAGE  1
*****************************************************************************************************************

                    CROSS SECTION PROFILE

                 LENGTH    ELEV.     SLOPE      ROUGHNESS

        1       -2670.0   -34.0
                                     97.50        1.00
        2       -1500.0   -22.0
                                     76.25        1.00
        3        -585.0   -10.0
                                     72.50        1.00
        4        -150.0    -4.0
                                     36.43        1.00
        5         -99.0    -2.6
                                     42.22        1.00
        6          53.0     1.0
                                     24.64        1.00
        7         223.0     7.9
                                     39.60        1.00
        8         322.0    10.4
                                       .99        1.00
        9         335.0    23.5
                                     10.00        1.00
       10         350.0    25.0

                 LAST SLOPE   1.00     LAST ROUGHNESS   1.00
```

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**Table D-6. Output Example for the FEMA Wave Runup Model**

results of more immediate concern, in that the Wave Runup Model may calculate a runup elevation exceeding maximum barrier elevation; this outcome can occur because the program assumes the last positive slope to continue indefinitely. For bluffs or eroded dunes with negative landward slopes, a general rule has been used that limits the wave runup elevation to 3 feet above the maximum ground elevation. When the runup overtops a barrier such as a partially eroded bluff or a structure, the floodwater percolates into the bed and/or runs along the back slope until it reaches another flooding source or a ponding area. The runoff areas are usually designated as Zone AO with a depth of 1, 2, or 3 feet. Ponding areas are designated as Zone AH (depth of 3 feet or less) with a BFE. Standardized procedures for the treatment of sizable runoff and ponding are presented in Appendix E of these Guidelines.

A fairly typical situation on the Atlantic and Gulf coasts is that wave runup exceeds the barrier top and flows to another flooding source such as a bay, river, or backwater. It may not be necessary in this situation to compute overtopping rates and ponding elevations; only the flood hazard from the runoff must be determined. Simplified procedures have been used to determine an approximate depth of flooding in the runoff area (Williams, 1983). These procedures are illustrated in Figure D-15 and discussed below.

When the runup computed on the imaginary extension of the last positive slope is greater than or equal to 3 feet above the maximum ground elevation, the maximum runup shall be 3 feet above the ground crest elevation. This elevation decays to 2 feet above the ground profile at 50 feet behind the crest and continues at this depth until it encounters other flooding. Computed runup is not adjusted if it is less than 3 feet above the ground crest. In the same initial 50 feet, this elevation decays to 1 foot above the ground and continues at this depth until it encounters other flooding. The runoff area from the ground crest to the limit of the other flooding is designated Zone AO with the appropriate depth of flooding.

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A distinct type of overflow situation can occur at low bluffs or banks backed by a nearly level plateau, where calculated wave runup may appreciably exceed the top elevation of the steep barrier. A memorandum entitled “Special Computation Procedure Developed for Wave Runup Analysis for Casco Bay, FIS - Maine, 9700-153” provides a simple procedure to determine realistic runup elevations for such situations, as illustrated in Figure D-16 (French, 1982). An extension to the bluff face slope permits computation of a hypothetical runup elevation for the barrier, with the imaginary portion given by the excess height $R' = (R\text{-}C)$ between calculated runup and the bluff crest. Using that height $R'$ and the plateau slope $m$, Figure D-17 defines the inland limit to wave runup, $X$, corresponding to runup above the bluff crest of ($mX$) or an adjusted runup elevation of $R_a = (C + mX)$. This procedure is based on a Manning's "n" value of 0.04 with some simplifications in the energy grade line and is meant for application only with positive slopes landward of the bluff crest. A different treatment of wave overflow onto a level plateau, for possible FIS usage, is provided in “Overland Bore Propagation Due to an Overtopping Wave” (Cox & Machemehl, 1986).

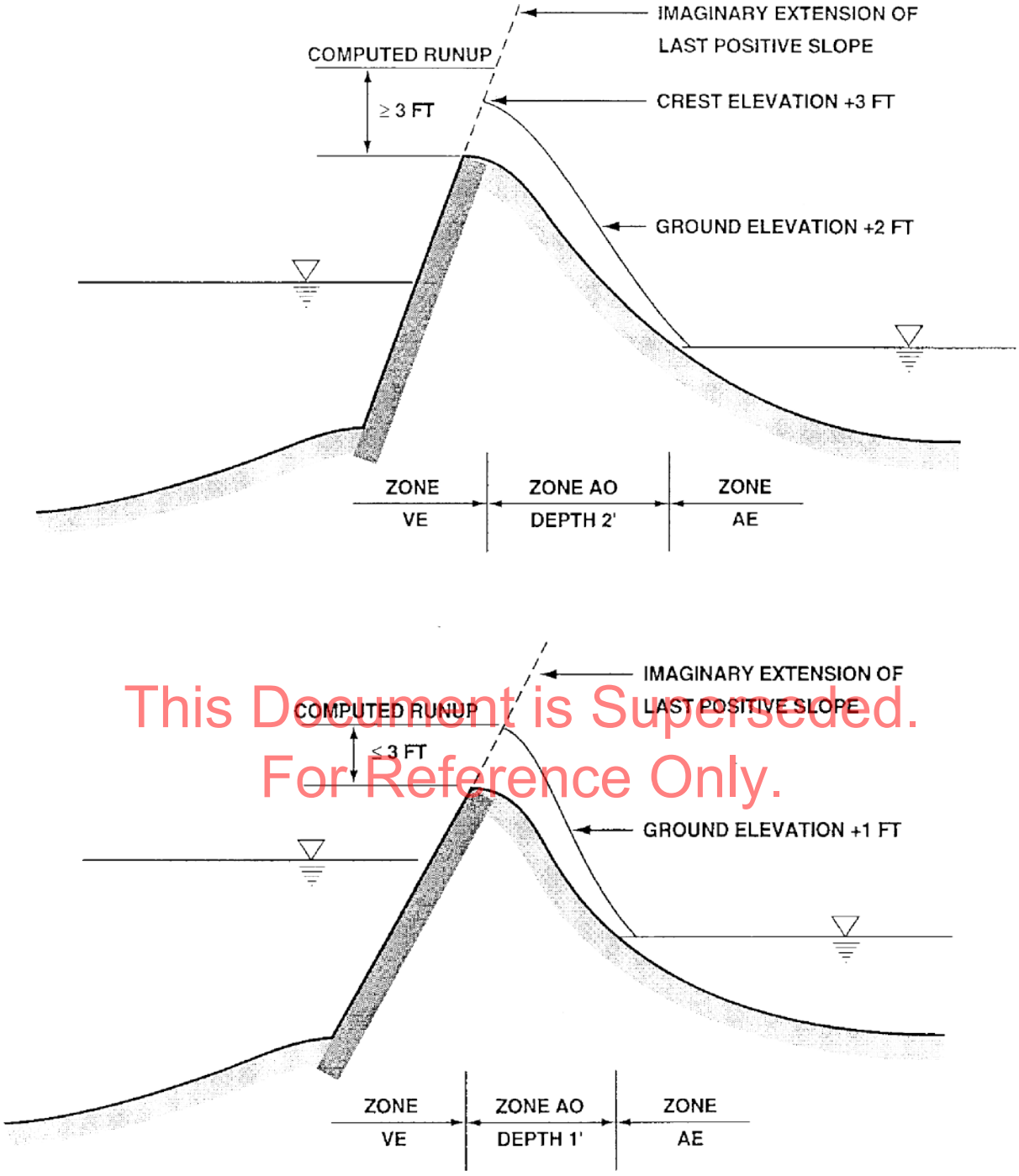


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**Figure D-15. Simplified Runoff Procedures (Zone AO)**

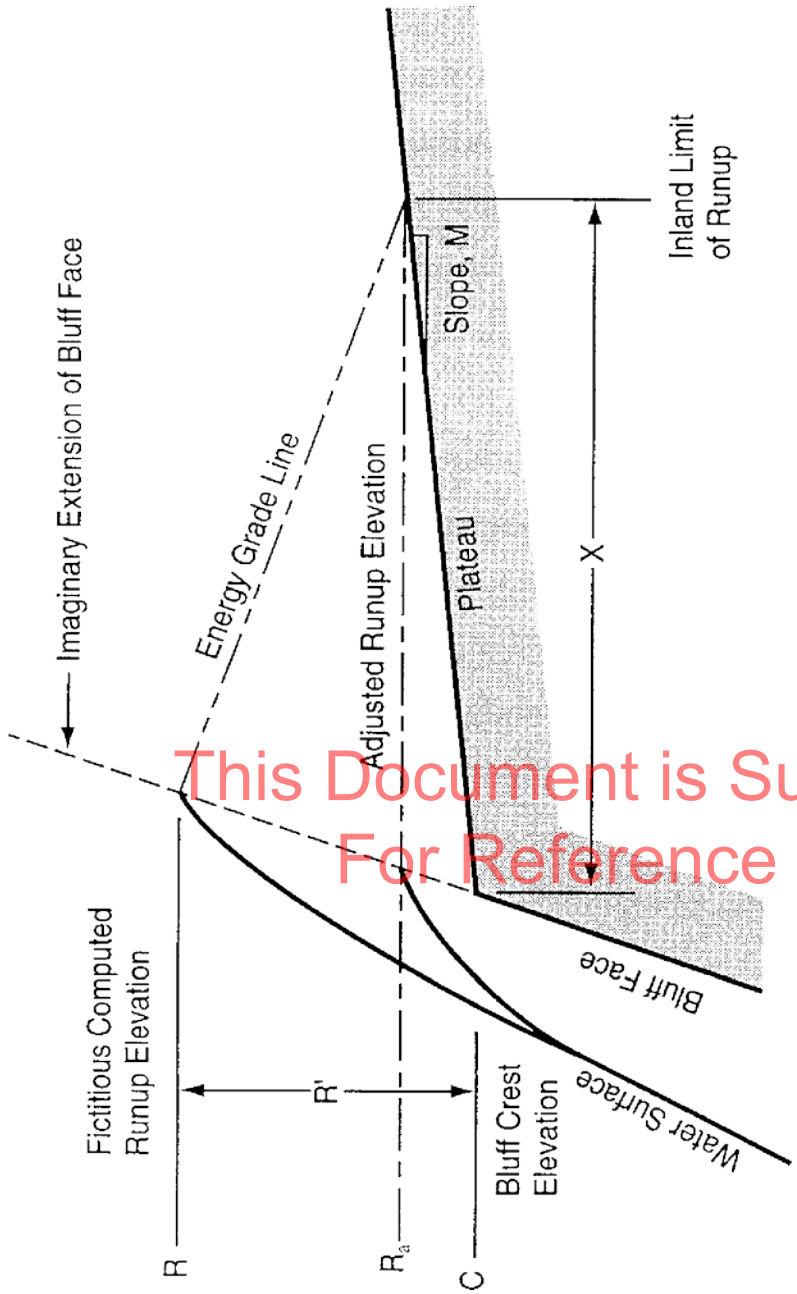


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**Figure D-16. Treatment of Runup onto Plateau above Low Bluff**

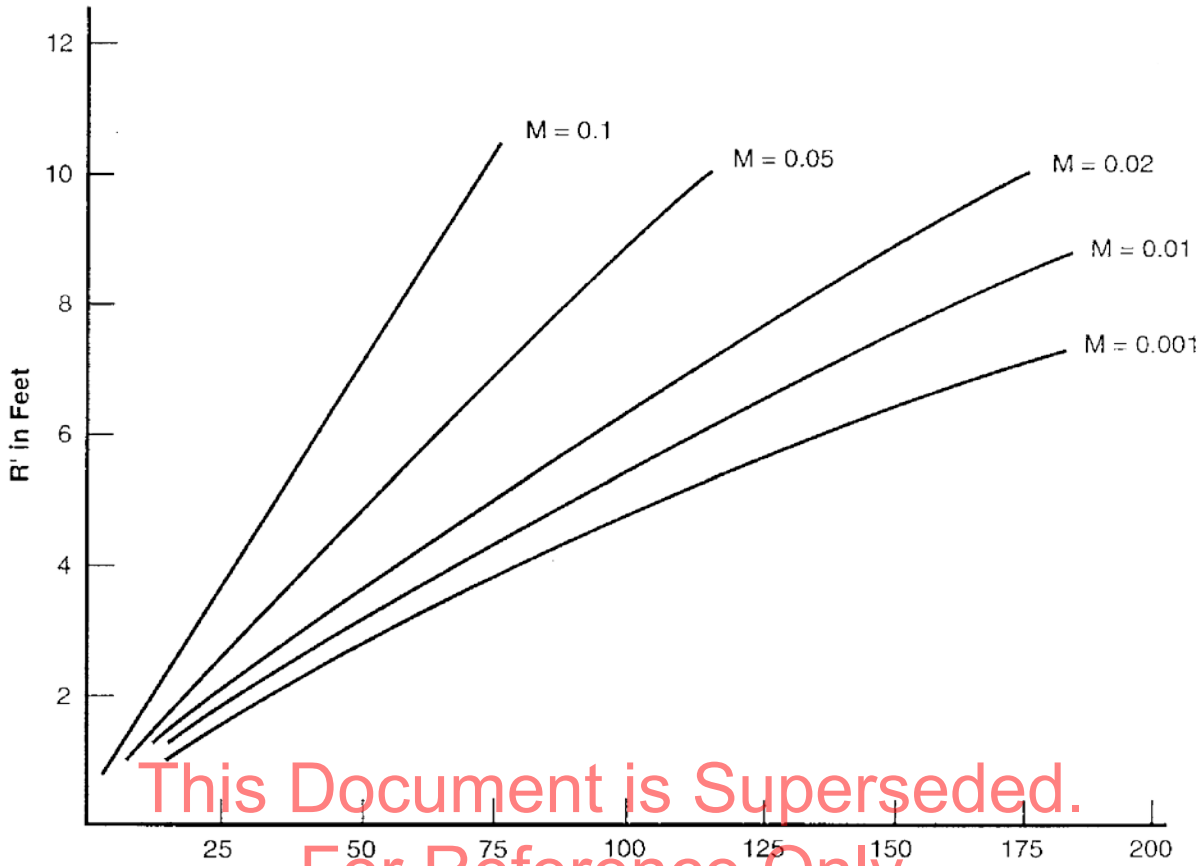


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**Figure D-17. Curves for Computation of Runup Inland of Low Bluffs**

These runup assessment procedures are given for general guidance, but situations may exist where they are not entirely applicable. For example, runup elevations need to be fully consistent with wave setup and wave overtopping assessments described in subsections that follow. In problematic cases, the Mapping Partner shall use good judgment and rely on the historical data to reach a solution about realistic flood hazards associated with a shore barrier. Subsection D.2.7 considers the integration of separately calculated wave effects into coherent hazard zonations for the 1-percent-annual-chance flood. When a unique situation is encountered, the Mapping Partner shall prepare a Special Problem Report and discuss it with the FEMA RPO.

[February 2002]

### D.2.5.6 Wave Setup

Nearshore wave action can increase mean water elevation in front of a shore barrier by the phenomenon called wave setup, which is related to wave attenuation by breaking in shallow water. In treating the 1-percent-annual-chance flood, focus may be restricted to the cumulative setup effect in the immediate vicinity of the shore barrier. Laboratory measurements of wave runup generally include the contribution due to wave setup, because runup elevations are defined relative to stillwater level in the absence of wave action.

A separate calculation for wave setup can be appropriate even if a wave runup elevation has already been determined, in part because the changed mean water depth can increase wave heights and crest elevations to be expected near the shore. In addition, empirical guidance within the Wave Runup Model is based on uniform laboratory wave action, so that incorporated setup might pertain to the field situation of swell waves from distant storms; setup effects may be much different in the local storm waves accompanying the 1-percent-annual-chance flood. If storm wave setup is found to exceed the wave runup calculated for a particular situation, the Mapping Partner shall apply the setup estimate as a lower bound for actual wave runup in further analysis of wave effects and 1-percent-annual-chance flood elevations.

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The USACE *Shore Protection Manual* provides straightforward empirical guidance on wave setup for various storm wave conditions and plane bottom slopes, as reproduced in Figure D-18 (USACE, 1984). Setup magnitude is given in dimensionless form, as normalized by incident significant wave height. This guidance, given typical significant storm-wave steepness of 0.03 to 0.04, indicates shore setups of 7 to 8 percent of incident wave height. Incident wave conditions are specified in deep water as the significant wave height and the wave steepness, $H_{os}/L_{op}$), where $L_p = gT_{op}^2 / 2\pi 5$ is wavelength in deep water. Bottom slope may be taken as an overall average over the breaker zone between $d = 2H_o$ and $d$=0, if the bottom geometry is relatively simple. For other geometries, e.g., with a berm or reef in front of the shore barrier, the wave setup can be larger than given by Figure 18 and a more detailed examination may be required.

Wave setup also appears appreciably larger according to an independent treatment of storm waves on plane slopes, as outlined for a relatively narrow spectrum describing incident wave energy in *Random Seas and Design of Maritime Structures* (Goda, 1985). If historical evidence indicates greater setup increases of mean water depth in extreme floods than Figure D-18 gives

for the study site, the Mapping Partner shall develop a wave setup estimate based on that independent guidance through the ACES computer program provided in *Automated Coastal Engineering System, Version 1.07* (Leenknecht, Szuwalski, & Sherlock, 1992). The program does not permit direct calculation of wave effects at d=0; however, the Mapping Partner may linearly extrapolate setup results from about $d=H_o$ to the shallow limit of computations to the stillwater shoreline.

[February 2002]

### D.2.5.7 Wave Overtopping

Wave overtopping results when a shore barrier does not contain incident wave action, so that floodwater penetrates to the protected area landward. This process of a partial halt and dissipation to storm waves is more difficult to treat than wave runup or wave setup. Important rates of wave overtopping can vary over several orders of magnitude, and can depend strongly on the detailed geometry of the barrier. That complicates the development of empirical guidance on wave overtopping, but little demand exists for such guidance in coastal engineering practice. According to *Criteria for Evaluating Coastal Flood-Protection Structures*, the design process for a major coastal flood protection structure relies on site-specific model testing, rather than generalized overtopping guidance (Walton, Ahrens, Truitt, & Dean, 1989).

Of course, the assessment of potential wave overtopping for present purposes must rely on readily available empirical guidance, historical effects, and engineering judgment. Except for very heavy overtopping, useful guidance is derived from tests with irregular waves, because the intermittently large overtopping discharges in storm situations could not be reproduced otherwise. Adding to the formal complexity of an adequate treatment for flood hazard assessment, overtopping effects may be cumulative so that the entire course of a flood event could require consideration, not just the peak conditions. However, the Mapping Partner shall estimate only the order of magnitude of overtopping rates because there are clearly documented thresholds below which wave overtopping may be classified as negligible. On the other hand, if a preliminary estimate indicates severe overtopping that threatens the stability of a given structure, that structure might be removed from the transect for analyses of the 1-percent-annual-chance flood, and no further overtopping consideration would be required.

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Two publications, *Design of Seawalls Allowing for Wave Overtopping* (Owen, 1980) and *Random Seas and Maritime Structures* (Goda, 1985) appear to provide the most trustworthy and wide-ranging summaries of mean overtopping rates with storm waves. The former publication addresses smooth plane or bermed slopes, and the latter publication considers vertical walls with or without a fronting rubble mound. Before surveying those primary sources of overtopping guidance, however, some introductory considerations can help to determine whether detailed assessment is needed for 1-percent-annual-chance flood conditions at a specific shore barrier.

The initial consideration is an interpretation of mean runup elevation already calculated ($\overline{R}$ 6), in terms of likely extreme elevations according to the Rayleigh probability distribution usually appropriate for wave runups. To parallel the extreme wave height addressed in coastal studies (NAS, 1977), a controlling runup magnitude may be defined as 1.6 times significant runup, or

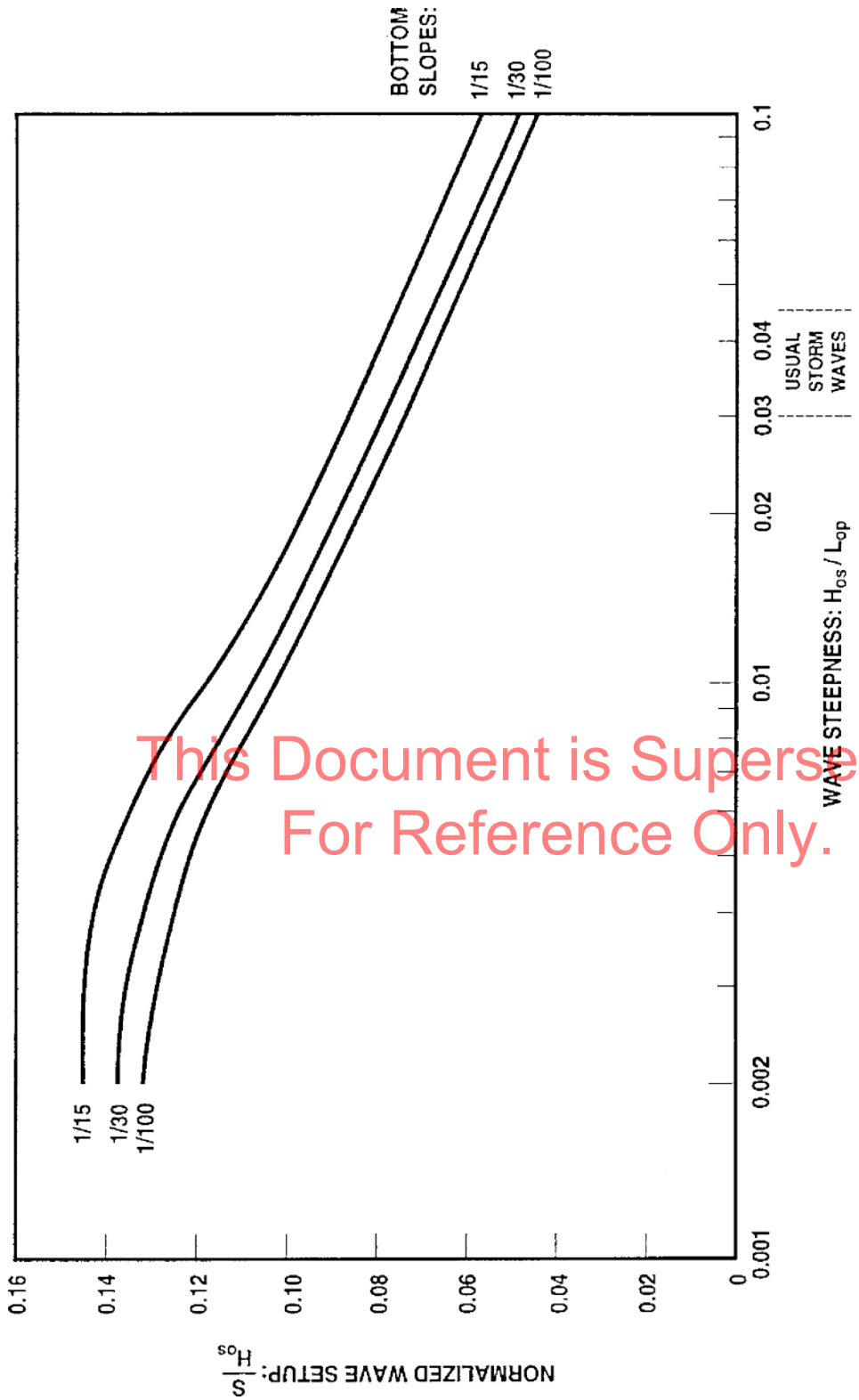


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**Figure D-18. Guidance on Wave Setup in Irregular Wave Action, From Shore Protection Manual (USACE, 1984)**

2.5 times mean runup according to the Rayleigh distribution. If elevation of the barrier crest above 1-percent-annual-chance SWEL, or the barrier freeboard $F$, equals or exceeds (2.5 $\overline{R}$ 7), then the landward area is not subject to wave-induced discharges during the 1-percent-annual-chance flood. That requirement might be supplemented by consideration of $F$ near (2 $\overline{R}$ 8), corresponding to 4.5 percent of the runup reaching the barrier crest according to the Rayleigh distribution. If $F \leq$ (2 $\overline{R}$ 9), wave overtopping can certainly be appreciable during the 1-percent-annual-chance flood, and the Mapping Partner shall assess ponding or runoff behind the barrier. The extreme runups introduced here, (2 $\overline{R}$ 10) and (2.5 $\overline{R}$ 11), bracket the elevation exceeded by the extreme 2 percent of wave runup, a value commonly considered in structure design.

Once the need for quantitative overtopping assessment is established, wave runup considerations become inapplicable because a runup elevation generally cannot be converted to an overtopping estimate. Also, the composite-slope method used in determining wave runup does not appear applicable for overtopping of barriers with composite geometry, because details of the wave transformation on a barrier influence the resultant overtopping rates. Wave overtopping estimates for a specified situation generally must be based on measurements in a similar configuration. Before considering some implications of quantitative guidance for idealized cases, an overview of overtopping magnitudes gives a useful introduction (Goda, 1985; Gadd, Potter, Safaie, & Resio, 1984).

Wave overtopping is specified as a mean discharge: water volume per unit time and per unit alongshore length of the barrier, commonly cfs/ft. By interpreting or visualizing a given overtopping rate, the Mapping Partner may take into account that the actual discharges generally are intermittent and isolated, being confined to some portion of occasional wave crests at scattered locations. Distinct regimes of wave overtopping may be described as spray, splash, runup wedge, and waveform transmission, in order of increasing intensity. Flood discharges corresponding to those regimes naturally depend on the incident wave size, but certain overtopping rates have been associated with various characteristics (Goda, 1985). Among those rates, 0.01 cfs/ft seems to correspond to flooding that generally should be considered appreciable, and 1 cfs/ft appears to define an approximate threshold where structural stability of the shore barrier commonly becomes threatened by severe overtopping.

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Once the mean overtopping rate has been estimated for the 1-percent-annual-chance flood, determining resultant flooding may require a representative duration for the interval of overtopping. That duration can vary widely depending on the coastal flood cause, from a fast-moving hurricane to a nearly stationary extratropical storm. A minimum assumption for the duration of flood-peak overtopping would generally be 1 to 2 hours. Durations of 10 hours or more could be appropriate for cumulative effects in an extratropical storm causing flooding over multiple high tides.

Figure D-19 summarizes some empirical overtopping guidance for storm waves, in a schematic form meant to assist deciding the likely significance of flooding behind a coastal structure. Variables describing the basic situation are cotangent of the front slope for a smooth structure with ideally simple geometry, and freeboard of the structure crest above stillwater level, as

normalized by incident significant wave height, $F/H_s$. The mean overtopping rate, $\overline{Q}$12, is provided in dimensionless form as

$$Q^* = \overline{Q}\,13/(gH_s^3)^{0.5} \tag{2}$$

with test results shown for structure slopes of 1:1, 1:2, and 1:4 (Owen, 1980) and for a smooth vertical wall (Goda, 1985). These results pertain to: significant wave steepness of approximately $2\pi H_s/gT_p^2 = 0.035$, fairly appropriate for extreme extratropical storms or hurricanes; water depth near the structure toe of approximately $d_t = 2H_s$, so that incident waves are not appreciably attenuated; and moderate approach slopes of 1:30 for a vertical wall or 1:20 for other structures. The major feature of interpolated curves is fixed as a maximum in overtopping rate for structure slope of 1:2, corresponding to the gentlest incline producing (at this wave steepness) total reflection rather than breaking, and thus peak waveform elevations (Nagai & Takada, 1972).

These measured results for smooth and simple geometries clearly show severe or "green water" overtopping even at relatively high structures ($F \geq H_s$) for a wide range of common inclinations (cotangents between 0 and 4). Also, for freeboards considered here, a vertical wall (cotangent 0) permits less overtopping than common sloping structures with cotangent less than approximately 3.5. Gentler barriers are uncommon because the construction volume increases with the cotangent squared, so steep coastal flood-protection structures usually face attenuated storm waves and/or have rough surfaces. Basic effects of those differences can be outlined for use in simplified overtopping assessments.

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For sloping structures sited within the surf zone ($d_t < 2H_s$), *Design of Seawalls Allowing for Wave Overtopping* indicates that basic overtopping guidance in Figure D-19 can be used with attenuated rather than incoming wave height (Owen, 1980). A simple estimate basically consistent with other analyses of the 1-percent-annual-chance flood is that significant wave height is limited to $H'_s = d_t/2$ at the structure toe. The value of $(2F/d_t)$ describes the effectively increased freeboard in entering Figure D-19, and the indicated Q* value is then converted to $\overline{Q}$ using $H'_s$. The presumed wave attenuation ignores any wave setup as a small effect with the partial barrier, and $d_t$ should always correspond to the scour condition expected in wave action accompanying the 1-percent-annual-chance flood.

Figure D-19 might also be made applicable to rough slopes, using a roughness coefficient ($r$) from Table D-3 to describe the effectively increased freeboard with greater wave dissipation on the structure. *Design of Seawalls Allowing for Wave Overtopping* proposed formulating effect of structure roughness as $F/r$, and *Beach and Dune Erosion during Storm Surges* confirmed a similar dependence of overtopping on roughness in measured results for irregular waves (Owen,

1980; Vellinga, 1986). The overtopping relation reported as reliable in "Wave Runup and Overtopping on Coastal Structures" is

$$Q^* = 8 \bullet 10^{-5} \exp[3.1(rR^* - F / H_s)] \quad (3)$$

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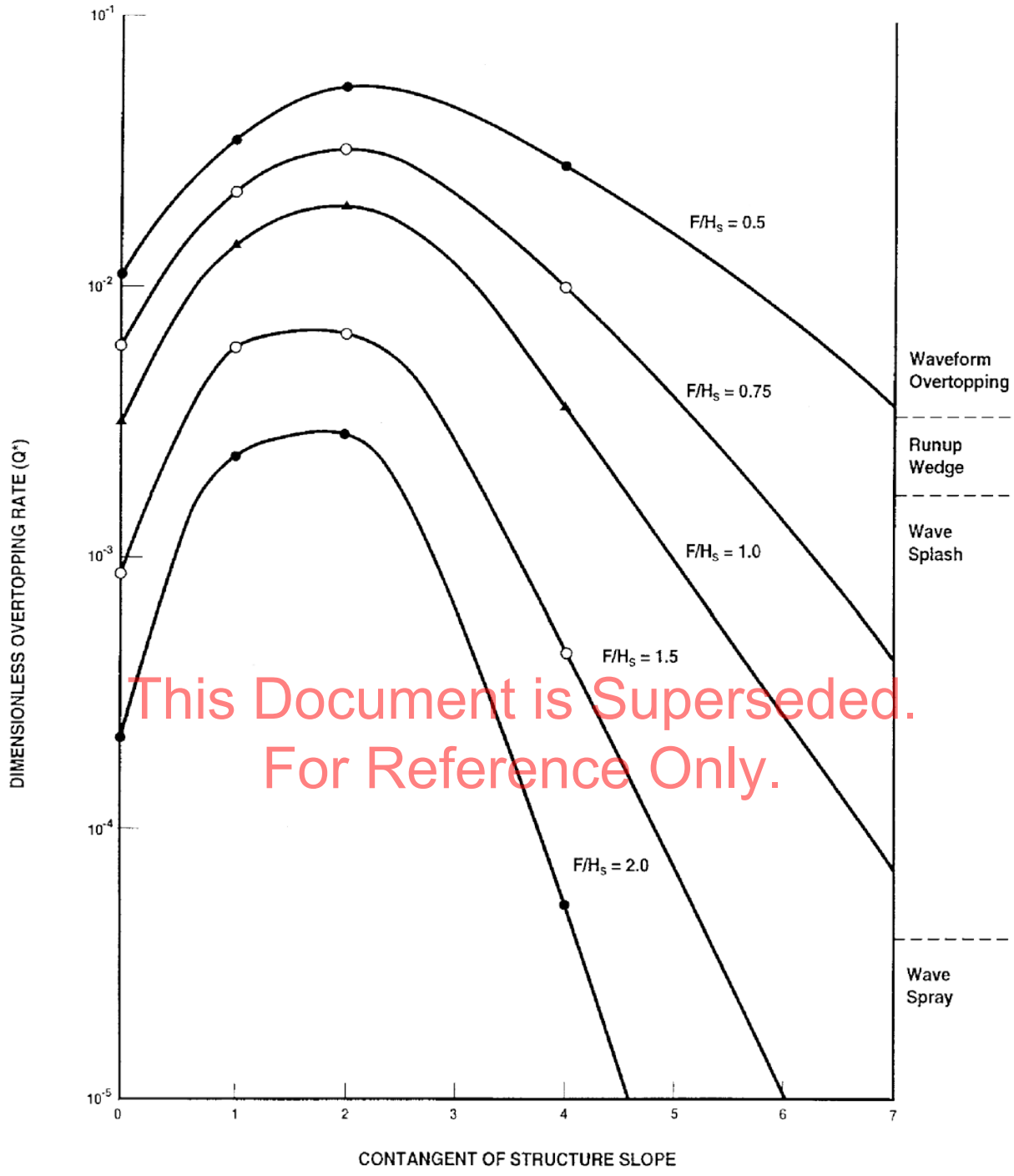


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**Figure D-19. Schematic Summary of Storm-Wave Overtopping at Structures of Various Slopes and Freeboards, Based on Goda, 1985, and Owen, June 1980.**

where $R_* = [1.5\ m/(H_s/L_{op})^{0.5}]$, up to a maximum value of 3.0, is an estimated extreme runup normalized by $H_s$, for a barrier slope given as the tangent $m$ (de Waal & van der Meer, 1992). Equation 3 is meant to pertain to very wide ranges of test situations with moderate overtopping, but appears very approximate in comparison with specific results for $r$=1 shown in Figure D-19. It may be advisable to evaluate Equation 3 for both smooth and rough barriers, then to use the ratio to adapt a value from Figure D-19 for the case with roughness. *Design of Seawalls Allowing for Wave Overtopping* (Owen, 1980) and "Wave Runup and Overtopping on Coastal Structures" (de Waal & van der Meer, 1992) provide further overtopping guidance on the effects of composite profiles, oblique waves, and shallow water with sloping structures.

For overtopping of vertical walls, effects of wave attenuation appear relatively complex, but *Random Seas and Design of Maritime Structures* (Goda, 1985) provides extensive empirical guidance on various structure situations with incident waves specified for deep water. Figure D-20 converts basic design diagrams for wave overtopping rate at a vertical wall, to display wall freeboard required for rates of 1 cfs/ft and 0.01 cfs/ft with various incident wave heights. Goda (1985) also provides a convenient summary on the effect of appreciable fronting roughness in storm waves: the required freeboard of a smooth vertical wall for a given overtopping rate is approximately 1.5 times that which is needed when a sizable mound having concrete block armor is installed against the wall. With this information, a specific vertical wall can be categorized as having only modest overtopping ($\overline{Q}14 < 0.01$ cfs/ft), intermediate overtopping, or severe overtopping ($\overline{Q}15 > 1$ cfs/ft) expected for the 1-percent-annual-chance flood. Likely runoff or ponding behind the wall must then be identified; severe overtopping requires delineation of the landward area susceptible to wave action and velocity hazard. Subsection D.2.7 outlines several common zonations of flood hazards near shore barriers in describing the integration of computed wave effects.

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Considering Figure D-20 with respect to common wall and wave heights, wave overtopping dangerous to structural stability appears the usual case during the 1-percent-annual-chance flood.

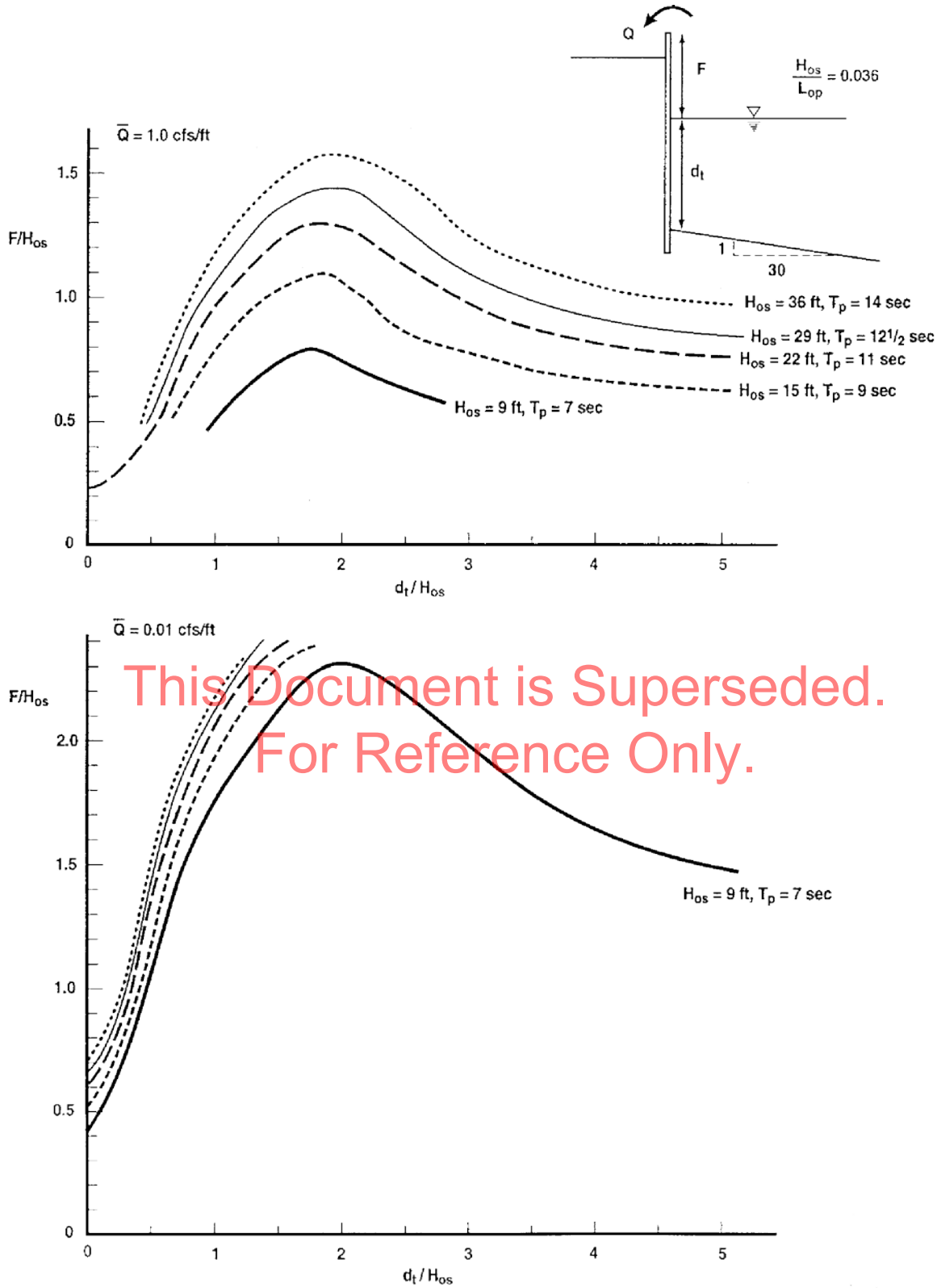


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**Figure D-20. Required Freeboard of Vertical Wall to Limit Mean Overtopping Rate to Certain Values, Based on Design Curves of *Random Seas and Design of Maritime Structures* (Goda, 1985)**

An assessment of failure during the 1-percent-annual-chance flood for typical walls would be fully consistent with one recommendation of *Criteria for Evaluating Coastal Flood-Protection Structures*: that "FEMA not consider anchored bulkheads for flood-protection credit because of extensive failures" (Walton et al., 1989).

Interpretation of estimated overtopping rate in terms of flood hazards is complicated by the projected duration of wave effects, by the increased discharge possible under storm winds, by the varying inland extent of water effects, and by the specific topography and drainage landward of the barrier. However, guidance is provided in Table D-7 as potentially applicable to typical coastal situations.

**Table D-7. Suggestions for Interpretation of Mean Wave Overtopping Rates**

| $\overline{Q}$16 ORDER OF MAGNITUDE | FLOOD HAZARD ZONE BEHIND BARRIER |
|---|---|
| <0.0001 cfs/ft | Zone X |
| 0.0001-0.01 cfs/ft | Zone AO (1 ft depth) |
| 0.01-0.1 cfs/ft | Zone AO (2 ft depth) |
| 0.1-1.0 cfs/ft | Zone AO (3 ft depth) |
| >1.0 cfs/ft* | 30-ft width+ of Zone VE (elevation 3 ft above barrier crest), landward Zone AO (3 ft depth) |

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*With estimated $\overline{Q}$17 much greater than 1 cfs/ft, removal of barrier from transect representation may be appropriate.

+Appropriate inland extent of velocity hazards should take into account structure width, incident wave period or wavelength, and other factors.

For each coastal structure experiencing sizable wave runup in the 1-percent-annual-chance flood (for example, $\overline{R}$18 > 2 ft), a brief report to the Project Officer should outline overtopping assessments and document conclusions consistent with historical evidence for the site.

[February 2002]

## D.2.6 Analysis of Overland Wave Dimensions

As water waves propagate near the shore and over flooded land, they can undergo marked transformations due to local winds, interaction with the bottom, and physical features such as buildings, trees, or marsh grass. Figure D-21 illustrates schematic effects on the wave crest elevations and on the type of flood zone. The fundamental analysis of wave effects for an FIS is provided by the WHAFIS 3.0 computer program, entitled "Wave Height Analysis for Flood Insurance Studies" (FEMA, 1988). This program or model calculates wave heights, wave crest elevations, flood hazard zone designations, and the location of zone boundaries along a transect.

Wave description for NFIP purposes addresses the controlling wave height, equal to 1.6 times the significant wave height common as a representative wave description. Significant wave

height is the average height of the highest one-third of waves, and controlling wave height is approximately the average height of the highest one percent of waves in storm conditions. The original basis for wave treatment under the NFIP was the NAS methodology, which accounted for varying fetch lengths, barriers to wave transmission, and the regeneration of waves over flooded land areas (USACE, 1975). Because of the introduction of the NAS methodology, periodic upgrades have been made to incorporate improved or additional wave considerations.

Technical details of the current WHAFIS model are fully documented *(Technical Documentation for WHAFIS Program Version 3.0*), but a brief overview indicates the level of wave treatment in WHAFIS 3.0 (FEMA, September 1988). A wave action conservation equation governs wave regeneration due to wind and wave dissipation by marsh plants. This equation is supplemented by the conservation of waves equation, which expresses the spatial variation of the wave period at the peak of the wave spectrum. The wave energy (equivalently, wave height) and wave period respond to changes in wind conditions, water depths, and obstructions as a wave propagates. These equations are solved as a function of distance along the transect. A predominant element in this wave treatment remains unchanged from the NAS methodology: controlling wave height is limited to 78 percent of the local mean water depth.

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### D.2.6.1 Use of WHAFIS 3.0 Model

Careful preparation and input of required site data are necessary in using WHAFIS. Like the other coastal treatments, the WHAFIS model considers the study area by representative transects. For WHAFIS, transects are selected with consideration given to major topographic, vegetative, and cultural features. The ground profile is defined by elevations referenced to NGVD and usually begins at elevation 0.0 and proceeds landward until either the ground elevation exceeds the meanwater elevation for the 1-percent-annual-chance flood or another flooding source is encountered.

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Other fundamental specifications among WHAFIS input include the 1-percent-annual-chance mean water elevation and a description of waves existing at the transect start. In the wave description, provision is made for an overwater fetch length, an initial significant wave height, or an initial period of dominant waves. In most applications, the wave period is the input description, because that parameter is readily available from information about offshore storm waves and the period does not change during most wave transformations. WHAFIS then computes an appropriate depth-limited wave height at the transect start. The only check necessary is to confirm that incident waves likely exceed that height and a wave condition limited by water depth occurs.

Different wave specifications can be appropriate for sites not on an open, straight coast. Where land shelter or wave refraction may result in reduced incident waves, it is appropriate to specify an initial significant wave height for the transect. Also, at sites on restricted water bodies, the overwater fetch length should be specified for likely wind direction at the flood peak. WHAFIS then computes an appropriate incident wave condition for the transect, but such waves are limited and any fetch length exceeding 24 miles yield the same results.

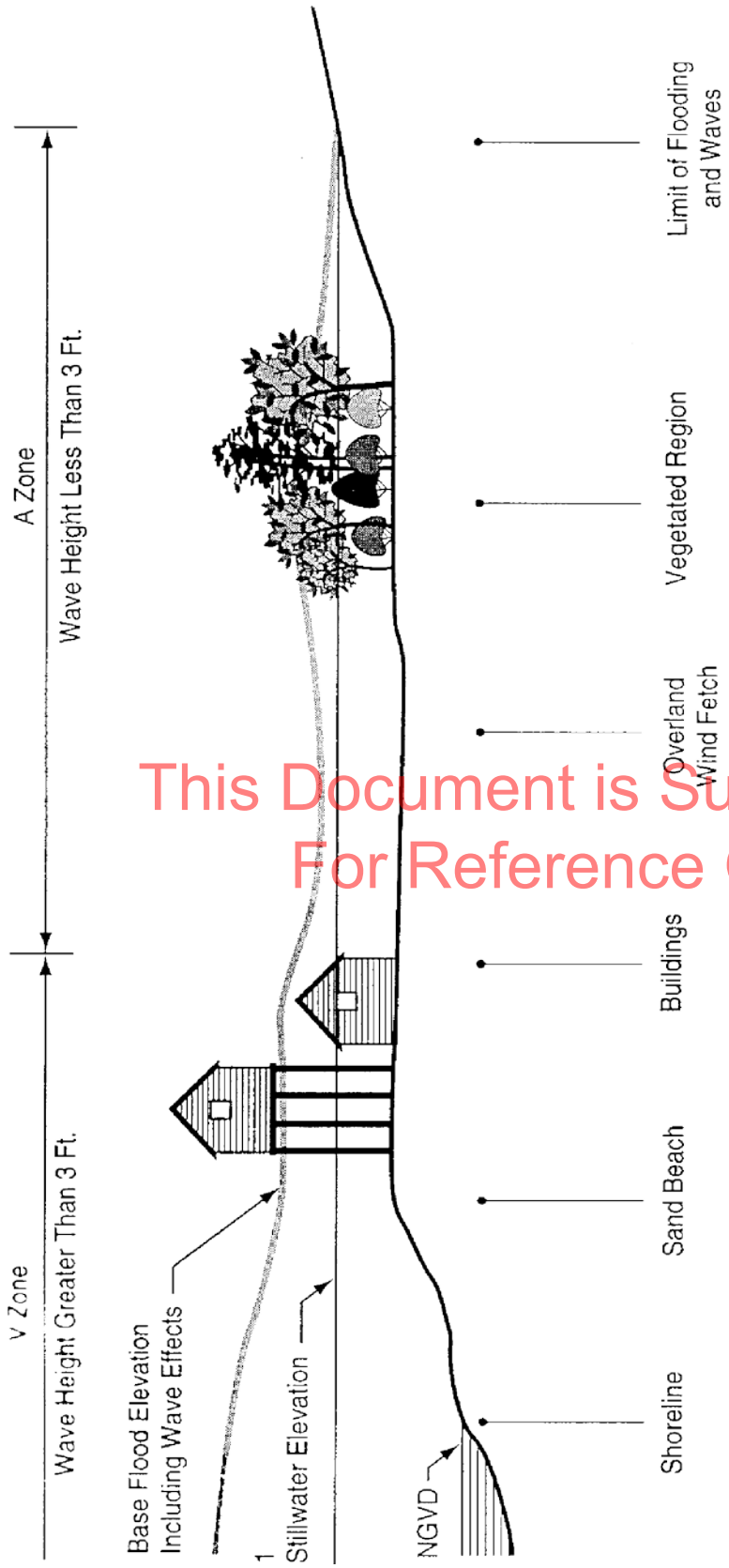


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**Figure D-21. Schematic Wave Effects on a Transect**

In preparing WHAFIS input, transects are to be located on the work maps and the transect ground profile is to be plotted from the topographic data, adjusted for erosion. Each transect is to have all the input data identified on the profile plot for ease of input coding. The location, height, and extent of elongated manmade structures is to be identified and shown as part of the ground profile, after the structure's stability under forces of the 1-percent-annual-chance flood is confirmed as discussed in Subsection D.2.3. When locating transects across barrier islands or sand spits, common practice is to continue the transect across the back bay and onto the mainland. If there is a large and/or unusually shaped embayment behind the island, it may be necessary to place additional transects just along the mainland shore. These transects may not parallel the transects from the open coast, and they may cross one another. The Mapping Partner shall keep crossing transects to a minimum; however, where it is not possible to avoid this, the transect determining greatest flood hazards shall control in mapping the flood hazards.

Once representative transects are located, the local 1-percent-annual-chance mean water levels can be defined for WHAFIS input. Wave setup should be included in this water elevation, as a part of the appropriate mean depth controlling wave dimensions (FEMA, September 1988). If wave setup was not calculated separately for the site, 1-percent-annual-chance SWEL is the appropriate specification. WHAFIS also has an input field for a 10-percent-annual-chance SWEL; however, it is only employed to determine Flood Hazard Factors, which FEMA no longer uses. Still, the Mapping Partner shall provide this input if it is readily available, because it could help in distinguishing between transects.

When a transect covers two or more flooding sources, the Mapping Partner shall identify an area of transition between the different SWELs. This is a common situation for barrier islands with ocean elevations on one side and bay elevations on the other side. It is usually assumed that the higher ocean elevations extend inland to the highest point of the reduced ground profile. WHAFIS performs a linear interpolation within a transect segment where elevations differ at the end stations. The interpolated elevations are compared to the ground elevations and adjusted, if necessary, to be above the ground elevations. The Mapping Partner may have to input the SWEL a second time to identify areas of constant elevation and elevation transition.

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The proper transect representation of some land features, particularly buildings and vegetation, merits further discussion. Buildings are specified on the transect as rows perpendicular to the transect. Because buildings are not always situated in perfect rows, the Mapping Partner shall exercise judgment to determine which buildings can be represented by a single row. The required input value for each row of buildings is the ratio of open space to total space. This is simply the sum of distances between buildings in a row, divided by the total length of that row. The Mapping Partner shall examine whether the first row or two of buildings along the shoreline should be considered as obstructions. During a 1-percent-annual-chance event, it is sometimes appropriate to assume that these buildings will be destroyed before the peak of the flood occurs if they are not elevated on pilings. If they are elevated, the waves should propagate under the structure with minimal reduction in height. It is useful to contact local officials to obtain typical construction methods and the lowest elevations of structures.

The WHAFIS program has two separate routines for vegetation: one for rigid vegetation that can be represented by an equivalent "stand" of equally spaced circular cylinders (NAS, 1977),

and one for marsh vegetation that is flexible and oscillates with wave action (FEMA, 1984). For either type, the Mapping Partner shall exercise considerable care in selecting representative parameters and in ruling out that the vegetation will be intentionally removed or that effects would be markedly reduced during a storm through erosion, uprooting, or breakage.

For the areas of rigid vegetation located on the transect, the required input values are the drag coefficient, $C_D$; mean wetted height, h; mean effective diameter, D; and mean horizontal spacing, b. The value of $C_D$ should vary between 0.35 and 1.0, with 1.0 being used in most cases of wide vegetated areas. When the vegetation is in a single stand, the Mapping Partner shall use a value of 0.35. The Mapping Partner may obtain representative values for h, D, and b from stereoscopic aerial photographs or by field surveys. Various guides for terrain analysis can provide advice on estimating values from aerial photographs. Table D-8 provides a useful process developed from *Terrain Analysis Procedural Guide for Vegetation* (Messmore, Vogel, & Pearson, 1979).

For marsh vegetation, a more complicated specification is required for completeness. The eight parameters used to describe the dissipational properties of a specific type are explained in Table D-9. However, WHAFIS incorporates considerable basic information on the eight common types of seacoast marsh plants listed in Table D-10 (FEMA, 1984). That information can be used either by specifying the Table D-10 abbreviation or a geographical region as indicated in Figure D-22. Figure D-22 shows the coastal wetland regions of the Atlantic and Gulf coasts, along with the identifying number used in WHAFIS. If the site is near a region border, the likely plant parameters can be interpolated using an input weighting factor. Although the South Texas region has insignificant amounts of marsh grass, it is included for usage in spatial interpolation.

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Climate affects the geographic range of each marsh plant type, so that some plant types are not found in all regions. Table D-11 lists the dominant plant type in each region, where the term "dominant" refers to the plant types that cover the largest amount of area in the marshes. Table D-12 shows the significant plant types in each region, where the term "significant" refers to the plant types that occur in large enough patches (at least 10,000 square feet) to significantly affect waves. For marsh plants, simply the coastal wetland region, plant type, and area or percent of coverage may be specified. Given this information, WHAFIS will supply default values for the other marsh plant parameters appropriate to the site (FEMA, 1984).

Following the identification of the marsh plant types present, the area and fraction of coverage, $F_{cov}$, for each plant type must be calculated. For each transect, the total area of marsh vegetation coverage is determined. The different types of vegetation within this area usually occur in patches. $F_{cov}$ is defined for each plant type as the ratio of the patch area for that type to the total marsh area. Using the above data, a fairly good determination can be made of the plant types present, but an attempt should be made to confirm these plant types. Local, county, or state officials may provide some assistance, and a site visit can be very useful.

**Table D-8. Procedures for Vegetation Analysis Using Stereoscopic Aerial Photographs.**

1. Using the parallax bar or wedge, determine the height of three representative trees and compute the average height, h.

2. Locate three representative tree crowns, measure the diameters, and compute the average crown diameter, CD.

3. Determine the type of vegetation and calculate the stem diameter, D, using the following formulae:

| | |
|---|---|
| Southern Pines | D (inches) = 5 + 0.5 CD (feet) |
| Eastern Hardwoods, Northern Pines and Others | D (inches) = 0.75 CD (feet) |

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4. Based on the scale of the aerial photographs, determine the diameter of a circle containing 0.08 hectares using Table 8a. Place the circle on the photograph, over a representative area of trees, and count the number of trees, n, in the circle. A magnifier may be needed. More than one area can be counted and an average used for n. Calculate the number of trees per hectare, N, using the following formula:

$$N = \frac{n}{0.08}$$

5. Determine the horizontal spacing between trees using the following formula:

$$b\ (feet) = (\frac{12732}{N} - \frac{D\ (inches)}{12}$$

**Table D-8. Procedures for Vegetation Analysis Using Stereoscopic Aerial Photographs (Cont.)**

(800 Square Meters, 8712 Square Feet)

| PHOTO SCALE | .08 HECTARE CIRCLE | CIRCLE DIAMETER | |
|---|---|---|---|
| | | INCHES | MILLIMETERS |
| 1:5,000 | | .253 | 6.38 |
| 1:6,000 | | .211 | 5.32 |
| 1:7,000 | | .1805 | 4.56 |
| 1:8,000 | | .158 | 3.99 |
| 1:9,000 | | .140 | 3.55 |
| 1:10,000 | | .126 | 3.192 |
| 1:11,000 | | .115 | 2.90 |
| 1:12,000 | | .105 | 2.66 |
| 1:13,000 | | .092 | 2.46 |
| 1:14,000 | | .090 | 2.28 |
| 1:15,000 | | .084 | 2.13 |
| 1:16,000 | | .079 | 1.99 |
| 1:17,000 | | .074 | 1.88 |
| 1:18,000 | | .070 | 1.77 |
| 1:19,000 | | .067 | 1.68 |
| 1:20,000 | | .063 | 1.60 |
| 1:21,000 | | .060 | 1.52 |
| 1:22,000 | | .057 | 1.45 |
| 1:23,000 | | .055 | 1.39 |
| 1:24,000 | | .053 | 1.33 |
| 1:25,000 | | .051 | 1.28 |

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**Table D-9. Marsh Plant Parameters**

| PARAMETER | EXPLANATION |
|---|---|
| $C_D$ | Effective drag coefficient. Includes effects of plant flexure and modification of the flow velocity distribution. Default value is 0.1, usually appropriate for marsh plants without strong evidence to the contrary. |
| $F_{cov}$ | Fraction of coverage. A default value is calculated by the program so that each plant type in the transect is represented equally, and the sum of the coverage for the plant types is equal to 1.0. |
| h | Unflexed stem height (feet). The stem height does not include the flowering head of the plant, the inflorescence. |
| N | Number density. Expressed as plants per square foot. The relationship to the average spacing between plants, b, can be expressed as $N = 1/b^2$. |
| $D_1$ | Base stem diameter (inches). Default value may be determined from stem height and regression equations built into the program. |
| $D_2$ | Mid stem diameter (inches). Default value may be determined from plant type and base stem diameter. |
| $D_3$ | Top stem diameter (inches), at the base of the inflorescence. Default value may be determined from plant type and base stem diameter. |
| $CA_b$ | Ratio of the total frontal area of the cylindrical portion of the leaves to the frontal area of the stem below the inflorescence. Default value may be determined from the plant type. |

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**Table D-10. Abbreviations of Marsh Plant Types used in WHAFIS**

| SPECIES OR SUBSPECIES | ABBREVIATION |
|---|---|
| *Cladium jamaicense* (saw grass) | CLAD |
| *Distichlis spicata* (salt grass) | DIST |
| *Juncus gerardi* (black grass) | JUNM |
| *Juncus roemerianus* (black needlerush) | JUNR |
| *Spartina alterniflora* (medium saltmeadow cordgrass) | SALM |
| *Spartina alterniflora* (tall saltmeadow cordgrass) | SALT |
| *Spartina cynosuroides* (big cordgrass) | SCYN |
| *Spartina patens* (saltmeadow grass) | SPAT |

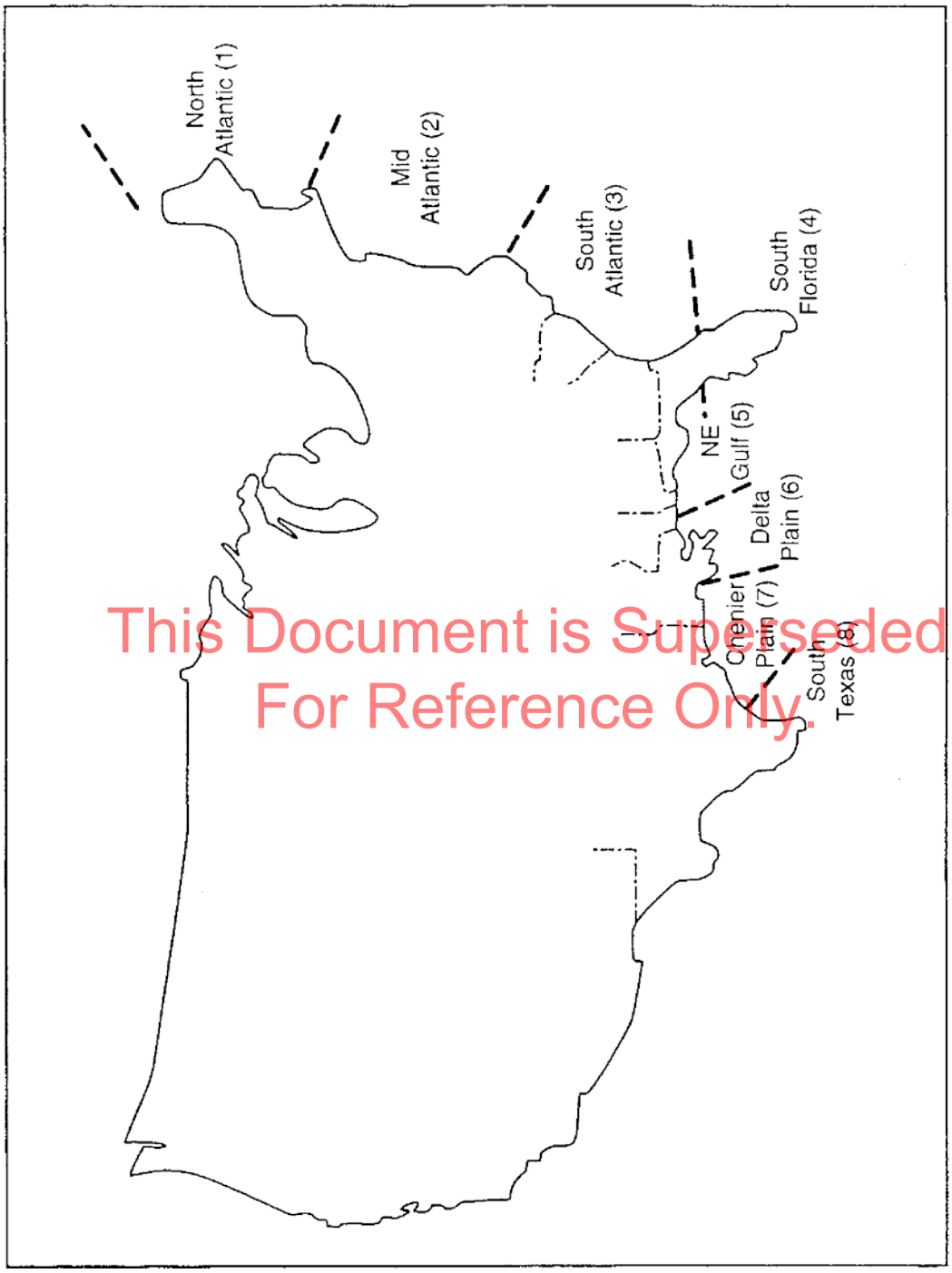


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**Figure D-22. Coastal wetland regions of Atlantic and Gulf coasts having enough marsh grass to significantly affect wave heights. Region numbers are indicated in parentheses.**

**Table D-11. Dominant Marsh Plant Types by Region and Habitat**

| REGION NUMBER | REGION NAME | HABITAT | DOMINANT SPECIES |
|---|---|---|---|
| 1 | North Atlantic | salt[1]<br>brackish[2] | **S. alterniflora* (medium, tall)<br>*Spartina patens* |
| 2 | Mid-Atlantic | salt<br>brackish | *S. alterniflora* (medium, tall)<br>**Juncus roemerianus/S. patens* |
| 3 | South Atlantic | salt<br>brackish | **S. alterniflora* (medium, tall)<br>*J. roemerianus* |
| 4 | South Florida | salt<br>brackish | *S. alterniflora* (medium, tall)<br>**C. jamaicense* |
| 5 | Northeastern Gulf | salt<br>brackish | ---<br>**J. roemerianus* |
| 6 | Delta Plain | salt<br>brackish | **S. Alterniflora* (medium, tall)<br>*S. patens* |
| 7 | Chenier Plain | salt<br>brackish | *S. alterniflora* (medium, tall)<br>**S. patens* |
| 8 | South Texas | salt<br>brackish | ---<br>--- |

[1]Salt concentration is greater than 20 parts per thousand (ppt)

[2]Salt concentration is between 5 and 20 ppt

*When more than one dominant plant type occurs within the region, the indicated type covers the largest geographic area (acreage)

--- Insignificant amounts of marsh plants within the given habitat in the region

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**Table D-12. Significant Marsh Plant Types in Each Seacoast Region and WHAFIS Default Regional Plant Parameter Data**

| REGION NO. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| REGION NAME: | NORTH ATLANTIC | MID-ATLANTIC | SOUTH ATLANTIC | SOUTH FLORIDA | NORTHEASTERN GULF | DELTA PLAIN | CHENIER PLAIN | SOUTH TEXAS |
| CLAD | --- | --- | --- | 7.50(+)<br>0.0656<br>6 | 6.00(2)<br>0.0260<br>6 | --- | --- | --- |
| DIST | --- | 0.78(1)<br>0.0039<br>211 | 1.00(1)<br>0.038<br>243 | 1.00(+)<br>0.0038<br>248 | ---<br>--- | 1.08(4)<br>0.0035<br>102 | 1.08(+)<br>0.0035<br>102 | --- |
| JUNM | 1.23(1)<br>0.0042<br>300 | 1.23(+)<br>0.0042<br>300 | --- | --- | --- | --- | --- | --- |
| JUNR | --- | 2.95(+)<br>0.0095<br>147 | 2.95(+)<br>0.0095<br>147 | --- | 2.95(3)<br>0.0095<br>147 | 3.00(4)<br>0.0106<br>83 | 2.95(+)<br>0.0095<br>147 | --- |
| SALM | 1.39(1)<br>0.0184<br>45 | 1.06(1)<br>0.0103<br>36 | 1.63(1)<br>0.0141<br>12 | 1.63(+)<br>0.0141<br>12 | --- | 1.67(4)<br>0.0141<br>21 | 2.62(5)<br>0.0211<br>16 | --- |
| SALT | 1.86(1)<br>0.0175<br>37 | 2.21(1)<br>0.0169<br>18 | 3.20(1)<br>0.0183<br>10 | 3.20(+)<br>0.0183<br>10 | --- | 3.20(4)<br>0.0183<br>10 | 3.20(+)<br>0.0183<br>10 | --- |
| SCYN | --- | --- | 8.29(+)<br>0.0492<br>6 | --- | --- | 4.00(4)<br>0.0267<br>7 | --- | --- |
| SPAT | 1.03(1)<br>0.0025<br>409 | 0.85(1)<br>0.0019<br>327 | 1.65(1)<br>0.0019<br>236 | --- | 2.58(2)<br>0.0026<br>236 | 1.88(4)<br>0.0016<br>333 | 1.88(+)<br>0.0019<br>333 | --- |

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Data arranged in vertical triplets:

h, stem height below inflorescence, in feet
D, base diameter, in feet
N, number density, in inverse square feet

Parenthetical references indicate data source:

1 = Hardisky and Reimold, 1977
2 = Monte, August 1983
3 = Kruczynski, Subrahmanyam, Drake, 1978
4 = Hopkinson, Gosselink, Parrondo, 1980, Diameters extrapolated
5 = Turner and Gosselink, 1975, Diameters extrapolated
+ = Extrapolated Data
--- = Insignificant amounts of this plant type in the region

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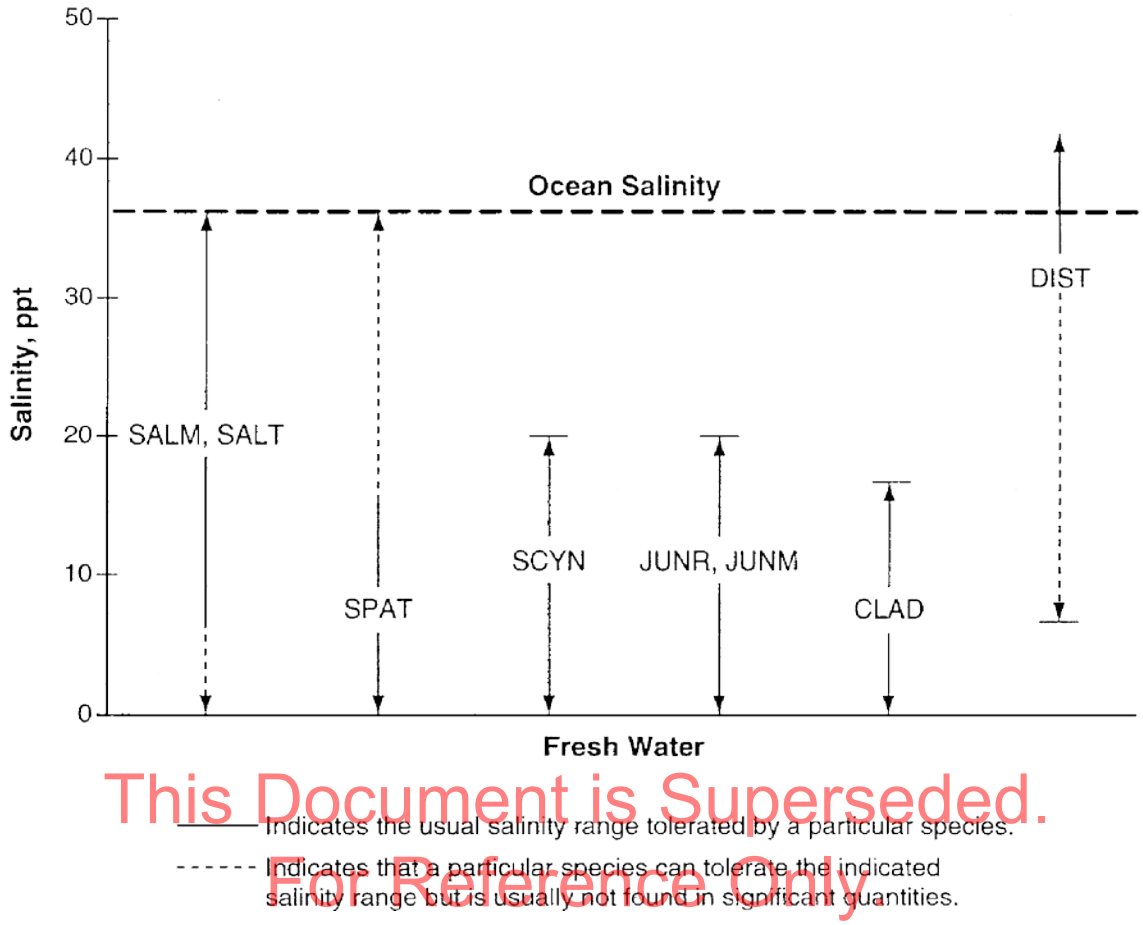


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**Figure D-23. Salinity Tolerance of Marsh Plants, from Knutson & Woodhouse, 1983**

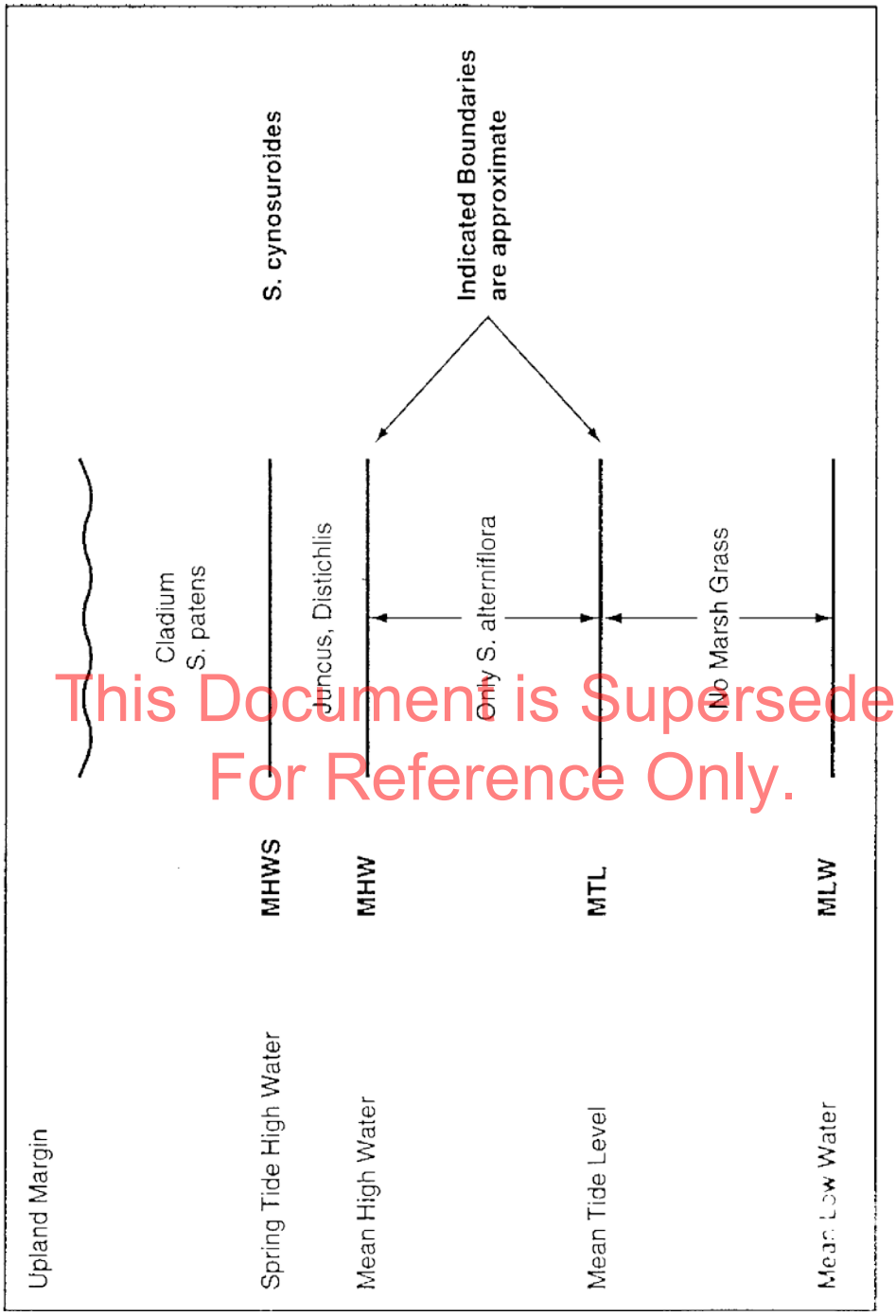


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**Figure D-24. Tidal Control on Salt Marsh Plant Viability**

### D.2.6.2 Input Coding for WHAFIS

After all the necessary input data have been identified on the transect, the Mapping Partner shall divide the transect into contiguous segments, each representing a continuous open fetch or a single obstruction. Fetches are flooded areas with no obstruction, while obstructions include dunes, manmade barriers, buildings, and vegetation. The Mapping Partner shall subdivide the fetches at points where the ground elevation abruptly changes and in the transition area of changing SWELs. The Mapping Partner shall subdivide obstructions into smaller segments at the transect's seaward edge to model the wave dissipation more accurately. Rigid vegetation shall have two to three seaward segments extending 10 to 50 feet, and the first two or three rows of buildings shall have a segment for each row. Marsh vegetation will be subdivided within WHAFIS, so segmented input from the Mapping Partner is not necessary.

The Mapping Partner shall enter the necessary data using 11 line types, including the Title line. The ten remaining lines, each describing a certain type of fetch or obstruction, are listed as follows:

- The IE (Initial Elevation) line describes the initial overwater fetch and the initial SWELs.
- The IF (Inland Fetch) and OF (Overwater Fetch) lines define the endpoint stationing and elevation of inland and overwater fetches, respectively.
- Obstructions are categorized either as buildings (BU line), rigid vegetation (VE line), marsh vegetation (VH and MG lines), dunes and other natural or manmade elongated barriers (DU line), or areas where the ground elevation is greater than the 1-percent-annual-chance SWEL (AS line).
- The ET (End of Transect) line enters no data but indicates the end of the input data.

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Each line has an alphanumeric field describing the type of input for that line, followed by ten numeric fields describing the parameters.

To ensure proper modeling, the Mapping Partner shall enter all segments of each transect either as fetches or obstructions, with one input line required for each fetch or obstruction segment. The first two columns of each line identify the type of fetch or obstruction. The remaining 78 columns consist of one field of six columns followed by nine fields of eight columns. The Mapping Partner shall right-justify the numbers in any data field only if no decimal point is used. Decimal points are permitted but not required. The end point of one fetch or obstruction is the beginning of the next. The first two numeric fields of each line are used to read in the stationing (measured in feet from the beginning of transect) and elevation (in feet) of the end point. The last two fields used on each line are for entering new SWELs. An interpolation is performed within a transect segment starting at the closest station with an input SWEL. This interpolation uses the new SWEL input at the end point of the segment and the SWEL input at a previous segment. If these fields are blank or zero, the SWELs remain unchanged.

The input data requirements are summarized below for each line type. The Title line must be the first line, followed by the IE line, followed by any combination of the various fetch and obstruction lines. The ET line must be the last card entered for the transect. A blank line must follow to signify the end of the run. If multiple transects are being run, the Title line for the next transect will follow the blank line. All units are in feet unless otherwise specified.

TITLE Line (Title)

This line is required and must be the first input line.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | Blank |
| 1-10 | 3-80 | Title information centered about column 40 |

IE Line (Initial Elevations)

This line is required and must be the second input line. This line is used to begin a transect at the shoreline and compute the wave height arising through the overwater fetch.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | IE |
| 1 | 3-8 | Stationing of end point of initial overwater fetch in feet (zero at beginning of transect) |
| 2 | 9-16 | Ground elevation at end point in feet (usually zero at beginning of transect) |
| 3 | 17-24 | Overwater fetch length (miles), if wave condition is to be calculated. Values of 24 miles or greater yield identical results. |
| 4 | 25-32 | 10-percent-annual-chance SWEL in feet |
| 5 | 33-40 | 1-percent-annual-chance SWEL in feet |
| 6 | 41-48 | Initial wave height in feet; a blank or zero causes a default to a calculated wave height |
| 7 | 49-56 | Initial wave period (seconds); a blank or zero causes a default to a calculated wave period. The period is usually the most convenient wave specification for open coasts. |
| 8-10 | 57-80 | Not used |

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AS Line (Above Surge)

This line is used to identify the end point of an area with ground elevation greater than the 1-percent-annual-chance SWEL (such as a high dune or other land mass). This is used when the ground surface temporarily rises above the 1-percent-annual-chance SWEL. The line immediately preceding the AS line must enter the stationing and elevation of the point at which the ground elevation first equals the 1-percent-annual-chance SWEL. SWEL on the inland side may differ from SWEL on the seaward side. The ground elevation entered on the AS line must

equal the SWEL that applies to the inland side of the land mass. Computer calculations will be terminated if a ground elevation greater than the 1-percent-annual-chance SWEL is encountered.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | AS |
| 1 | 3-8 | Stationing at end point in feet of area above 1-percent-annual-chance SWEL |
| 2 | 9-16 | Ground elevation in feet at end point |
| 3 | 17-24 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to the 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

BU Line (Buildings)

This line enters information needed to compute wave dissipation at each group of buildings.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | BU |
| 1 | 3-8 | Stationing of end point in feet of group of buildings |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | Ratio of open space between buildings to total transverse width of developed area |
| 4 | 25-32 | Number of rows of buildings |
| 5 | 33-40 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 6 | 41-48 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 7-10 | 49-80 | Not used |

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DU Line (Dune)

This line enters information necessary to compute wave dissipation over flooded sand dunes and other natural or manmade elongated barriers (e.g., levees and seawalls).

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | DU |
| 1 | 3-8 | Stationing at top of dune or barrier in feet |
| 2 | 9-16 | Elevation at top of dune or barrier in feet |
| 3 | 17-24 | A blank or zero indicates a dune or other natural barrier; any other number indicates a seawall or other manmade barrier |
| 4 | 25-32 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 5 | 33-40 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; |

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| | | otherwise new 1-percent-annual-chance SWEL |
| 6-10 | 41-80 | Not used |

IF Line (Inland Fetch)

This line enters the parameters necessary to compute wave regeneration through somewhat sheltered fetches and over shallow inland water bodies. The IF regeneration is computed using a sustained wind speed of 60 mph.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | IF |
| 1 | 3-8 | Stationing at end point of fetch in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

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OF Line (Overwater Fetch)

This line enters the parameters necessary to compute wave regeneration over large bodies of water (i.e., large lakes, bays) using a sustained wind speed of 80 mph. If an inland body of water is sheltered and has a depth of ten feet or less, the IF line calling for reduced wind speed should be used.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | OF |
| 1 | 3-8 | Stationing at end point of fetch in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

## VE Line (Vegetation)

This line enters parameters necessary to compute wave dissipation due to rigid vegetation stands.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | VE |
| 1 | 3-8 | Stationing at end point of vegetation in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | Mean effective diameter of equivalent circular cylinder in feet |
| 4 | 25-32 | Average actual height of vegetation in feet |
| 5 | 33-40 | Average horizontal spacing between plants in feet |
| 6 | 41-48 | Drag coefficient; a blank or zero causes a default to 1.0 |
| 7 | 49-56 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 8 | 57-64 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 9-10 | 65-80 | Not used |

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## VH Line (Vegetation Header for Marsh Grass)

Marsh grass is often part of a plant community that may consist of several types. The VH line is used to enter data that apply to all plant types modeled in the transect segment. To enter data for each plant type, MG lines for each plant type must follow the VH line.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | VH |
| 1 | 3-8 | Stationing at end point of marsh vegetation segment in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | $Reg_p$, number of the primary seacoast region for default plant parameters. See Figure 22. |
| 4 | 25-32 | $Wt_p$, weighting factor for the primary seacoast region. |
| 5 | 33-40 | $Reg_s$, number of secondary seacoast region. See Figure D-22. |
| 6 | 41-48 | $N_{p1}$, number of plant types; range is 1 to 10, inclusive. One MG line is required for each plant type. |
| 7 | 49-56 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 8 | 57-64 | A blank or zero indicates no change to the 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 9 | 65-72 | Not used |
| 10 | 73-80 | This field is for overriding the default method of averaging flood hazard factors |

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| | | in A Zones; if 1 in column 80, averaging process begins or ends at end of vegetation segment; otherwise, default averaging method is used |

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MG Line (Marsh Grass)

This line is used to enter data for a particular plant type. The first MG line must be preceded by a VH line. For the common seacoast marsh grasses listed in Table D-10, some potentially useful default values are supplied in Table D-12, and the program can provide additional default values (FEMA, October 1984). If a plant type not listed in the table is used, then appropriate data must be developed for Fields 2-9.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | MG |
| 1 | 5-8 | Marsh plant type abbreviation (see Table 10) |
| 2 | 9-16 | $C_D$, effective drag Coefficient; default value is 0.1 |
| 3 | 17-24 | $F_{cov}$, decimal fraction of vegetated area to be covered by this plant type; a blank or zero causes a default to be calculated so that each plant type is represented equally |
| 4 | 25-32 | h, mean unflexed height of stem (feet); for marsh plants, the inflorescence is not included |
| 5 | 33-40 | N, number of plants per square foot |
| 6 | 41-48 | $D_1$, base stem diameter (inches) |
| 7 | 49-56 | $D_2$, mid stem diameter (inches) |
| 8 | 57-64 | $D_3$, top stem diameter (inches) |
| 9 | 65-72 | $CA_b$, ratio of the total frontal area of cylindrical part of leaves to frontal area of main stem |
| 10 | 73-80 | Not used |

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ET Line (End of Transect)

This line is required and must be the last input card because it identifies the end of input for the transect.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | ET |
| 3-10 | 3-80 | Not used |

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### D.2.6.3 Error Messages

The error messages that may appear when running the model are described below.

- "AS card ground elevation less than SWEL, should use other type card, job dumped."

  Only use AS (above surge) line when the ground elevation is above the SWEL. Can otherwise use IF, OF, BU, DU, VE, or VH.

- "Ground elevation greater than surge elevation encountered, job dumped."

If ground elevation is above surge elevation, AS card should be used.

- "Average depth less than or equal to zero, job dumped."

  The water depth must be greater than zero or a wave height cannot be computed. Check the SWEL and the ground elevation if point of job dump is not the last point along the transect profile.

- "The above card contains illegal data in the first 2 columns."

  Check input data for incorrect values or input within wrong columns. Aside from the title line, the first two columns in each line should contain the card identifiers.

- "Transmitted wave height at last fetch or obstruction = _____ which exceeds 0.5."

  Code the transect profile up to the inland limit where ground elevation intersects the SWEL so that wave height should decrease to zero. If the scope of work ends at the corporate limits before the ground elevation meets the SWEL, this message can be ignored.

- "Array dimensions exceeded. Job dumped."

  Size of the array is limited and the number of input parameters has exceeded the array. Check the number of input parameters at the location where the job dumped.

- "Invalid data in field 1 of IF card," etc.

  Check input data to make sure that data are in correct columns.

- "Wave period less than or equal to zero in subroutine fetch. Abort run."

  Either a fetch length or a wave period must be input for the program to run properly. Check input data.

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- "Invalid data in field 3 or field 5 of VH card."

  Check input data.

- "Invalid data in field 4 of VH card."

  Check input data.

- "Invalid data in field 3 of MG card."

  Check input data. The fraction of vegetated area covered by the stated plant type should be a decimal number between 0.0 and 1.0.

- "Missing MG card or incorrect data in field 6 of VH card."

  A MG card must always follow the VH card. Field 6 of the VH card pertains to the number of plant types, and one MG card is required for each plant type.

- "Invalid input data."

  Check input data for invalid characters, such as an O instead of a zero. Check to be sure that all data are in their correct columns.

- "Fcov was found to be negative for plant type = _____."

  Check input data to be sure that the decimal fraction of the vegetated area covered by the plant type is not negative.

- "Ncov is .LE. zero in Sub.Lookup when it should be .GT. zero. Abort run."

  Check input for number of plants covering the area.

- "The first card is not an IE card, this transect is aborted. Continued to next transect."

  The first card after the title line must always be an IE card. Check input data.

- "**** The surge elevation at this station (stationing ____), which is ____ card, is less than the ground elevation. The interpolation process is continued. *** Please double check the surge and ground elevations in the vicinity of this station"

  The surge elevation should not be below the ground elevation. If the interpolated surge elevation is interpolated below the ground elevation, insert additional cards to specify surge and ground elevations and use an AS card if necessary.

- "Interpolation line cuts off more than two portions of high ground ridge. This transect is aborted, re-assign 1-percent-annual-chance elevations at high ground stations."

  When the interpolated value falls below the ground elevation, insert additional cards to better model the area and set the SWEL equal to the ground elevation where appropriate. Insert AS cards as necessary.

- "**** Unreasonable high ground elevation at station ____ which is ____ card. This transect is aborted, continued to next transect. **** Double check the surge and ground elevations in the vicinity of this station. If the ground elevations are correct, either assign a higher surge elevation or use AS cards."

  Add additional input data as necessary to better define the ground elevation and surge elevation in this area.

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### D.2.6.4 Output Description

The output of the program provides all the data necessary for plotting the BFEs and flood insurance risk zones along the transect. The output is in six parts:

**Part 1 - Input**

This is a printout showing all input data lines and the parameters assigned to each line, both manually and by default. This is followed by a more detailed printout with column headings for each input data line. When VH and MG Lines are used, a separate insert will be printed directly beneath the MG Line showing any default values supplied by the computer.

**Part 2 - Controlling Wave Heights, Spectral Peak Wave Period, and Wave Crest Elevations**

This is a list of the calculated controlling wave heights, spectral wave peak periods, and wave crest elevations at the end point of each fetch and obstruction of the input, and at calculation points generated between the input stations.

**Part 3 - Location of Areas Above 1-Percent-Annual-Chance Surge**

This is a list of the locations of areas where the ground elevation is greater than the 1-percent-annual-chance stillwater (surge) elevation. Only areas identified by AS lines are listed.

**Part 4 - Location of Surge Elevations**

This is a list of the 10- and 1-percent-annual-chance stillwater (surge) elevations and the stationing of the points where each set of SWELs first becomes fully effective.

**Part 5 - Location of V Zones**

This is a list of the locations of the V/A Zone boundary and locations of the V Zone areas relative to these boundaries. The stationing is given for each V/A Zone boundary. The locations of the V Zone areas in relation to these boundaries are given as windward or leeward of the boundary.

**Part 6 - Numbered A Zones and V Zones**

This is a list of the zone data needed to delineate the flood hazard boundaries on the FIRM. The location of a flood zone boundary and the wave crest elevation at that boundary are given on the left. Between the boundary listings are the zone designations and FHFs. Under FEMA's Map Initiatives Procedure guidelines, all numbered V and A Zones should be changed to VE and AE Zones, respectively (elevations will not change), and the FHFs can be ignored (FEMA, 1991). When the same zone and elevation are repeated in the list, they should be treated as a single zone.

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## D.2.7 Mapping of Flood Elevations and Zones

Requirements for reviewing the initial model results and identifying flood insurance risk zones, guidance and examples for determining transects, and guidance for depicting the analysis on the FIRM are presented in this subsection.

[February 2002]

### D.2.7.1 Review and Evaluation of Basic Results

Prior to mapping the flood elevations and zones, the Mapping Partner shall review results from the models and assessments from a common-sense viewpoint and compare them to available historical data. When using these models, there is the potential to forget that the transects represent real shorelines of sandy beaches, rocky or cohesive bluffs, wetlands being subjected to extremely high water, waves, and winds. Familiarity and experience with the coastal area being modeled or similar areas should provide an idea of what is a "reasonable" result.

Use of the historical data is also very important in evaluating whether the results are reasonable. It would be very convenient if data from a storm closely approximating the 1-percent-annual-chance event were available, but this is seldom the case. Although most historical flood data are

for storms less intense than a 1-percent-annual-chance event, these data will still indicate, at a minimum, what areas should be in flood zones. For instance, if a storm that produced an extreme flood below the 1-percent-annual-chance SWEL generally caused structural damage to houses 100 feet from the shoreline, a "reasonable" Zone VE width must be at least 100 feet. Similarly, houses that collected flood insurance claims for the same storm should be at least in a Zone AE, AH, or AO. If the analyses of the 1-percent-annual-chance flood produce flood zones and elevations indicating lesser hazards than those recorded for a more common storm, the analyses should be reevaluated. One possible explanation can be that a new coastal structure acts to reduce flood hazards locally.

If there are indications that a reevaluation is needed, the Mapping Partner shall determine whether the results of the erosion assessment are appropriate. The Mapping Partner shall attempt to compare the eroded profile to past effects, whether in the form of profiles, photographs, or simply descriptions. A general idea of what happened previously can be sufficient. The Mapping Partner shall use judgment and experience to project previous storm effects to the 1-percent-annual-chance conditions and to ensure that the eroded profile is consistent with previous events.

The Mapping Partner shall examine other data input to the assessments of wave effects. This includes checking that the SWELs, wave heights, wave periods, and fetch lengths were used correctly and are consistent with the historical data. Further consideration might be given to examining if the buildings or structures modeled would be destroyed by the storm or if the buildings are on pilings above the flooding.

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The main point to be emphasized here is that the results should not be blindly accepted. There are many uncertainties and variables in coastal processes during an extreme flood and many possible adjustments to methodologies for treating such an event. The validity of any model is demonstrated by its success in reproducing recorded events. Therefore, the model results must be in basic agreement with past flooding patterns, and historical data must be used to evaluate these results.

[February 2002]

### D.2.7.2 Identification of Flood Insurance Risk Zones

The Mapping Partner shall identify the flood insurance zones and BFEs including wave heights be identified on each transect plot before delineating the flood insurance zones on the work maps, because of additional wave effects along with the 1988 redefinition of Coastal High Hazard Area to include the primary frontal dune. The existing topography, eroded transect, combination of shore effects in the wave envelope, and other results from wave overtopping assessment are all important to the proper identification of flood insurance risk zones.

Specifically, as discussed in Subsection D.2.1.2, the existing ground profile defines an appropriate extent of the primary frontal dune, as a ridge of sand bounded by relatively steep slopes. As discussed in Subsection D.2.4.5, the eroded transect for cases of duneface retreat may imply that flood hazards due to wave overtopping extend into an area landward of the WHAFIS results. In addition, as discussed in Subsection D.2.5.7, wave overtopping of stable shore barriers can result in flooding to areas above the mean elevation of wave runup. However, the

main consideration for integrated treatment of wave-controlled flood elevations is to define the wave envelope joining height and runup effects.

This wave envelope is a combination of representative wave runup elevation with the controlling wave crest profile determined by WHAFIS. The wave crest profile is plotted on the transect from the data in Part 2 of the WHAFIS output. A horizontal line is extended seaward from the wave runup elevation to its intersection with the wave crest profile to obtain the wave envelope, as shown in Figure D-25. If the runup elevation is greater than the maximum wave crest elevation, the wave envelope will be a horizontal line at the runup elevation. Conversely, if the wave runup is negligible or was not modeled, the wave crest profile becomes the wave envelope.

Flood insurance risk zones are defined basically by the wave envelope along with the general zone descriptions in Table D-13. Those results are supplemented by runup and overtopping considerations, as introduced previously. The following material outlines the process of flood insurance risk zone identification, with specific examples presented in the next section to illustrate some usual results.

**Table D-13. Descriptions of Coastal Flood Insurance Risk Zones**

| | |
|---|---|
| Zone VE | Coastal High Hazard Areas where wave action and/or high-velocity water can cause structural damage in the 1-percent-annual-chance flood. These areas are primarily identified by: (1) the area where 3-foot or greater wave height could occur (this is the area where the WHAFIS wave crest profile is 2.1 feet or more above the SWEL), (2) the area where the eroded ground profile is 3 feet or more below the representative runup elevation, and (3) the entire primary frontal dune, by definition. Subdivided into elevation zones with BFEs assigned. |
| Zone AE | Areas of inundation by the 1-percent-annual-chance flood, including wave heights less than 3 feet and runup elevations less than 3 feet above the ground. These areas are also subdivided into elevation zones with BFEs assigned. |
| Zone AH | Areas of shallow flooding or ponding, with water depths of 1 to 3 feet. These areas are usually not subdivided, and a BFE is assigned. |
| Zone AO | Areas of sheet-flow shallow flooding where overtopping water flows into another flooding source. These areas are designated with 1-, 2-, or 3-foot depths of flooding. |
| Zone X | Areas above 1-percent-annual-chance flood inundation. On the FIRM, shaded Zone X is inundated by the 0.2-percent annual chance flood, unshaded Zone X is above the 0.2-percent annual chance flood. |

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For a complete listing of flood insurance risk zones, refer to Section 1.4.2.7.1 of Volume 1 of these Guidelines.

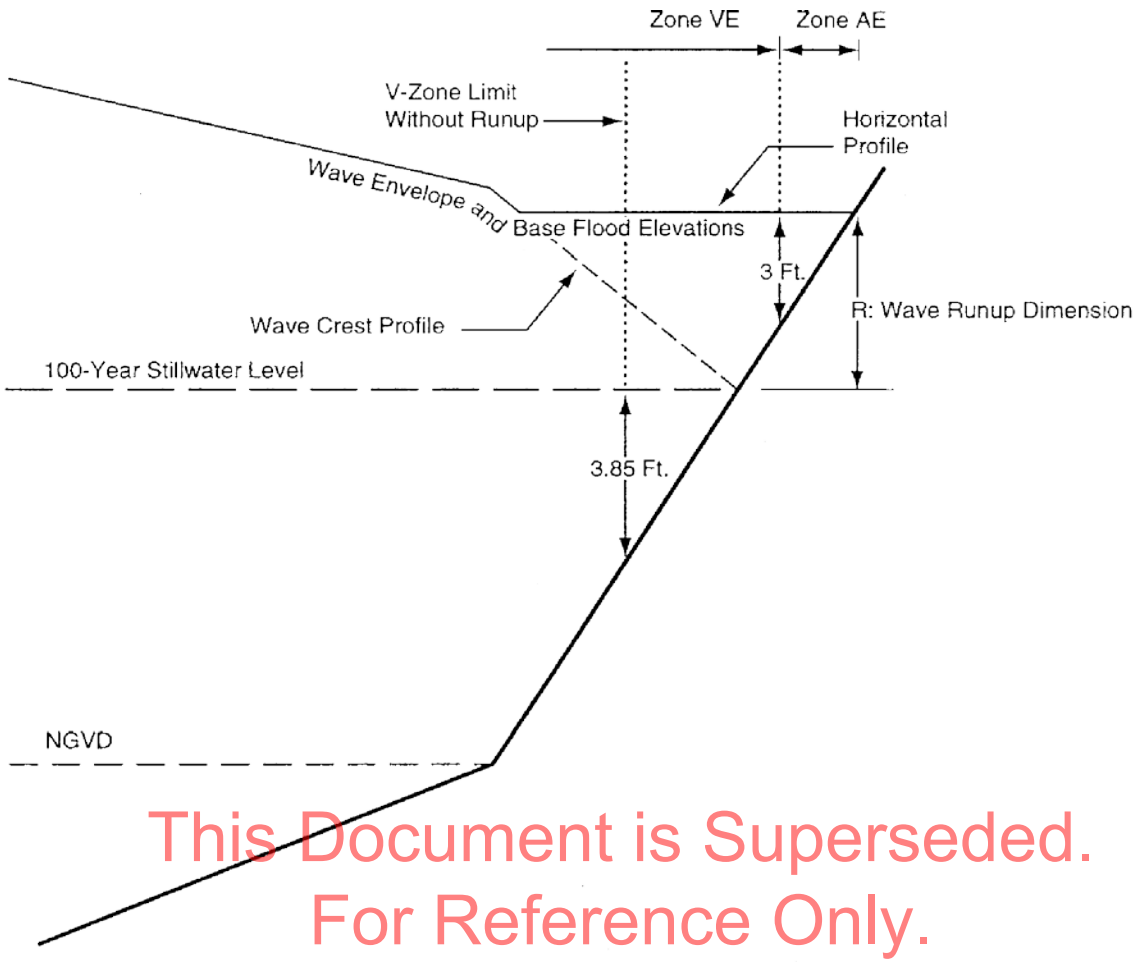


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**Figure D-25. Wave Envelope Resulting from Combination of Nearshore Crest Elevations and Shore Runup Elevation**

The first step in identifying the flood insurance risk zones on the transect is locating the inland extent of the VE Zone, also known as the VE/AE boundary. The VE-Zone limit for each of the three criteria is identified, and the VE/AE boundary placed at the one furthest landward, as shown in Figure D-26. The Mapping Partner may need to move that boundary further inland in the vicinity of a wave barrier where severe overtopping is indicated for the 1-percent-annual-chance flood, so high-velocity impacts occur over a limited landward area.

The Mapping Partner shall extend the Zone AE from the VE/AE boundary to the inland limit of 1-percent-annual-chance inundation, which is a ground elevation equal to the representative runup elevation, or the 1-percent-annual-chance SWEL if runup is negligible. The Mapping Partner may designate additional areas of shallow flooding or ponding for the 1-percent-annual-chance event as Zone AH or Zone AO. In cases of severe wave overtopping effects, a VE Zone may abut areas designated as Zone AH or Zone AO. The Mapping Partner shall label all areas above the 1-percent-annual-chance inundation as Zone X.

The Mapping Partner shall then subdivide the Zone AE and VE areas into elevation zones with whole-foot BFEs assigned according to the wave envelope. Ideally, the Mapping Partner would establish an elevation zone for every BFE in the wave envelope; but because these zones are mapped on the FIRM so that buildings or property can be located in a flood insurance risk zone, the Mapping Partner shall use a minimum width for the mapped zone to provide a usable FIRM. For coastal areas, the minimum zone width is 0.2 inch on the FIRM. For identifying elevation zones on the transect, the minimum width is 0.2 times the final FIRM scale; for example, a width of 80 feet for a FIRM at a scale of 1 inch equals 400 feet, or a width of 100 feet for a FIRM at a scale of 1 inch equals 500 feet.

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The Mapping Partner shall not subdivide the horizontal runup portion of the wave envelope, if any; the runup elevation, rounded to the nearest whole foot, is the BFE. The Mapping Partner shall subdivide the WHAFIS wave crest profile. Generally, the VE Zone is subdivided first. Initially, the Mapping Partner shall mark the location of all elevation zone boundaries on the transect. Because whole-foot BFEs are being used, these should always be at the location of the half-foot elevation on the wave envelope.

The Mapping Partner shall combine elevation zones that do not meet the minimum width with an adjacent zone or zones to yield an elevation zone wider than the minimum. The BFE for this combined zone is a weighted average of the combined zones. Often, in subdividing VE Zones, the maximum BFE is located just inside the mapped shoreline, and the remainder of the VE Zone is then subdivided into elevation zones of the minimum width.

The Zone AE, if wide enough, shall be subdivided in the same manner. If the total AE Zone is less than the minimum width, the lowest elevation VE Zone is usually assigned to that area. This situation typically occurs for steep or rapidly rising ground profiles, and it is not unreasonable to designate the entire inundated area as a VE Zone. In some cases, however, it may be appropriate for the Mapping Partner to extend the AE Zone slightly into the next zone seaward in order to satisfy the minimum width requirement.

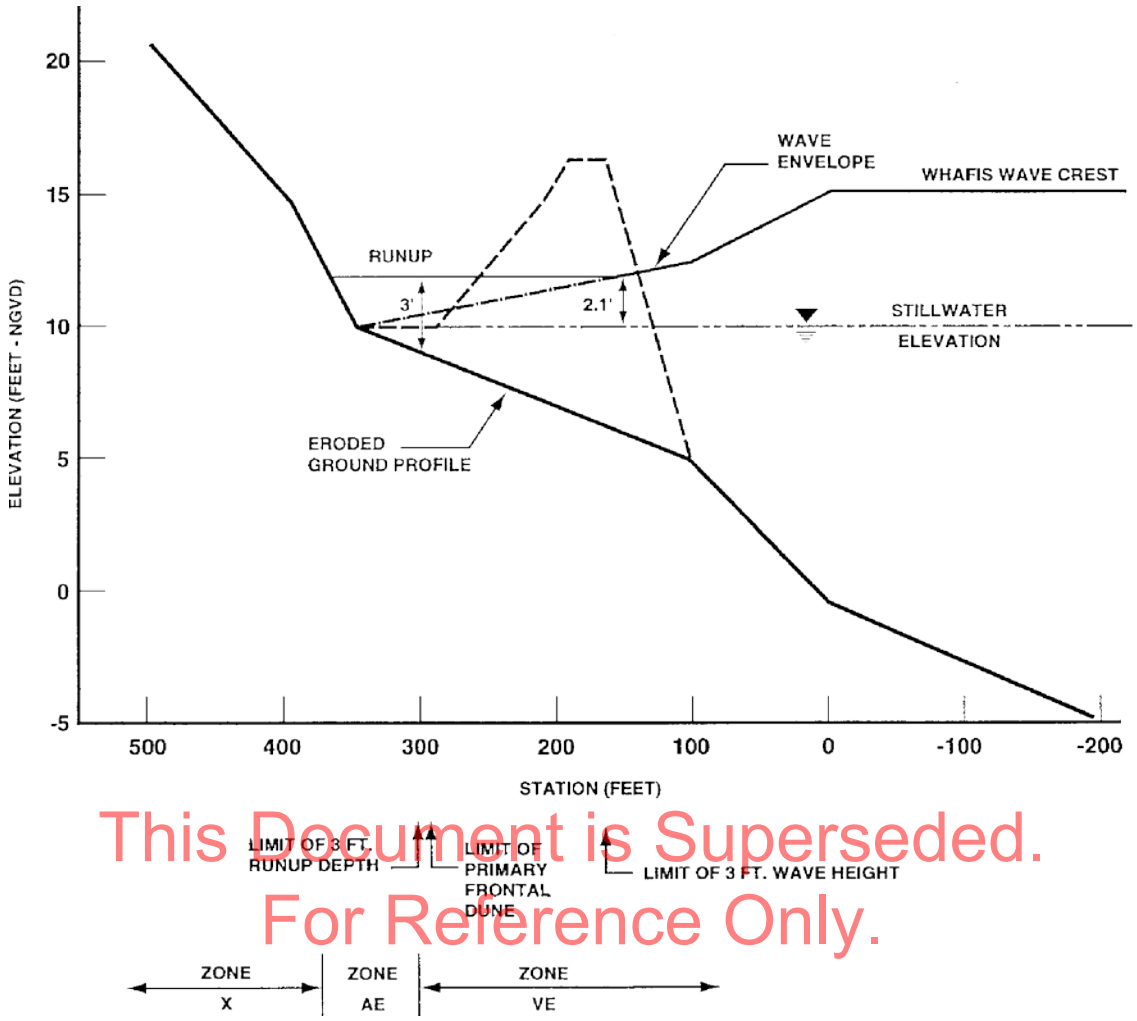


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**Figure D-26. Possible V-Zone Limits at Eroded Dune**

Relatively low areas inland of zones with assigned wave elevations may be subject to shallow flooding or ponding of flood water; the Mapping Partner shall designate these areas as Zone AH or Zone AO. Such designations can be relatively common landward of coastal structures and dunes, where wave overtopping occurs. Identifying appropriate zones and elevations may require particular care for dunes, given that the entire primary frontal dune is defined as Coastal High Hazard Area. Although the analyses may have determined a dune will not completely erode and wave action should stop at the retreated duneface with only overtopping possibly propagating inland, the Mapping Partner shall designate the entire dune as Zone VE. The Mapping Partner shall assign the BFE at the duneface for the remainder of the dune.

It may seem unusual to use a BFE that is lower than the ground elevation, although this is actually fairly common. Most of the BFEs for areas where the dune was assumed to be eroded are also below existing ground elevations. In these cases, it is the VE Zone designation that is most important to the NFIP, under current regulations, structures in VE Zones must be built on pilings and prohibits alterations to the dune.

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### D.2.7.3 Transect Examples

Figure D-26 provides a schematic summary for the three criteria potentially defining the landward limit to the Coastal High Hazard Area. The examples discussed below depict idealized transects of typical types to illustrate common flood hazard zonations in a quantitative way. Coastal erosion is a dominant consideration for the first set of examples. The second set of examples addresses some usual effects at stable shore barriers exposed to extreme wave action.

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Figure D-27 presents an example of dune removal with appreciable runup occurring on the eroded profile. For this transect, the VE Zones with BFEs of 13, 14, and 15 feet are too narrow to be mapped, so they are averaged to a BFE of 14 feet. The Zone VE, elevation 12 feet, is enlarged slightly to include some of the elevation 13-foot area so that the boundary would be located at the dune toe or 5-foot contour line, a feature easily identified on the work map. The boundary between the Zone VE, elevation 14 feet and the Zone VE, elevation 16 feet is located just landward of the shoreline. The Zone AE, elevation 12 feet, in Figure D-27 is only 70 feet wide, slightly less than the minimum mapping width. In this example, the Mapping Partner would have to examine the work map to determine if this zone might be wider or narrower in the contiguous area. If wider, the Zone AE should be used; if narrower, the designation extended through this area should be Zone VE, elevation 12 feet.

Figure D-28 illustrates an example of a relatively high retreated duneface. A mean runup elevation of 13 feet is calculated for the eroded duneface. This elevation is assigned through the dune, all of which is designated as Zone VE. Because the dune remnant extends more than 7 feet above the SWEL, no flooding landward of the dune is indicated by designating the area as Zone X. Note that the retreated dune profile shifts the 0.0 foot elevation shoreline 65 feet seaward. Because the existing 0.0 foot elevation shoreline is used on the work map, the Zone VE, elevation 16 feet, is located just landward of the existing shoreline.

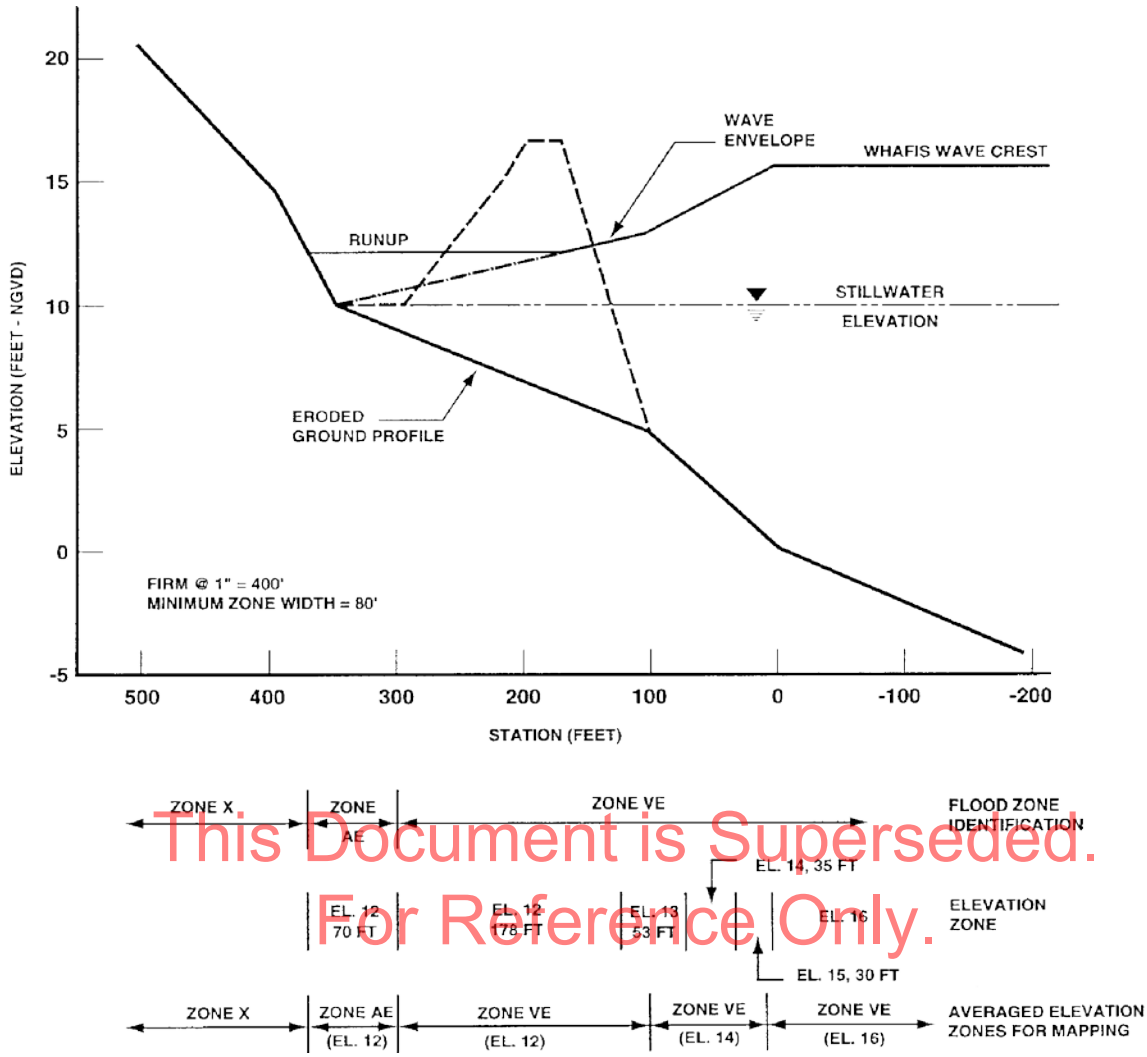


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**Figure D-27. Identification of Elevation Zones, Example 1: Dune Removal with Wave Runup Landward**

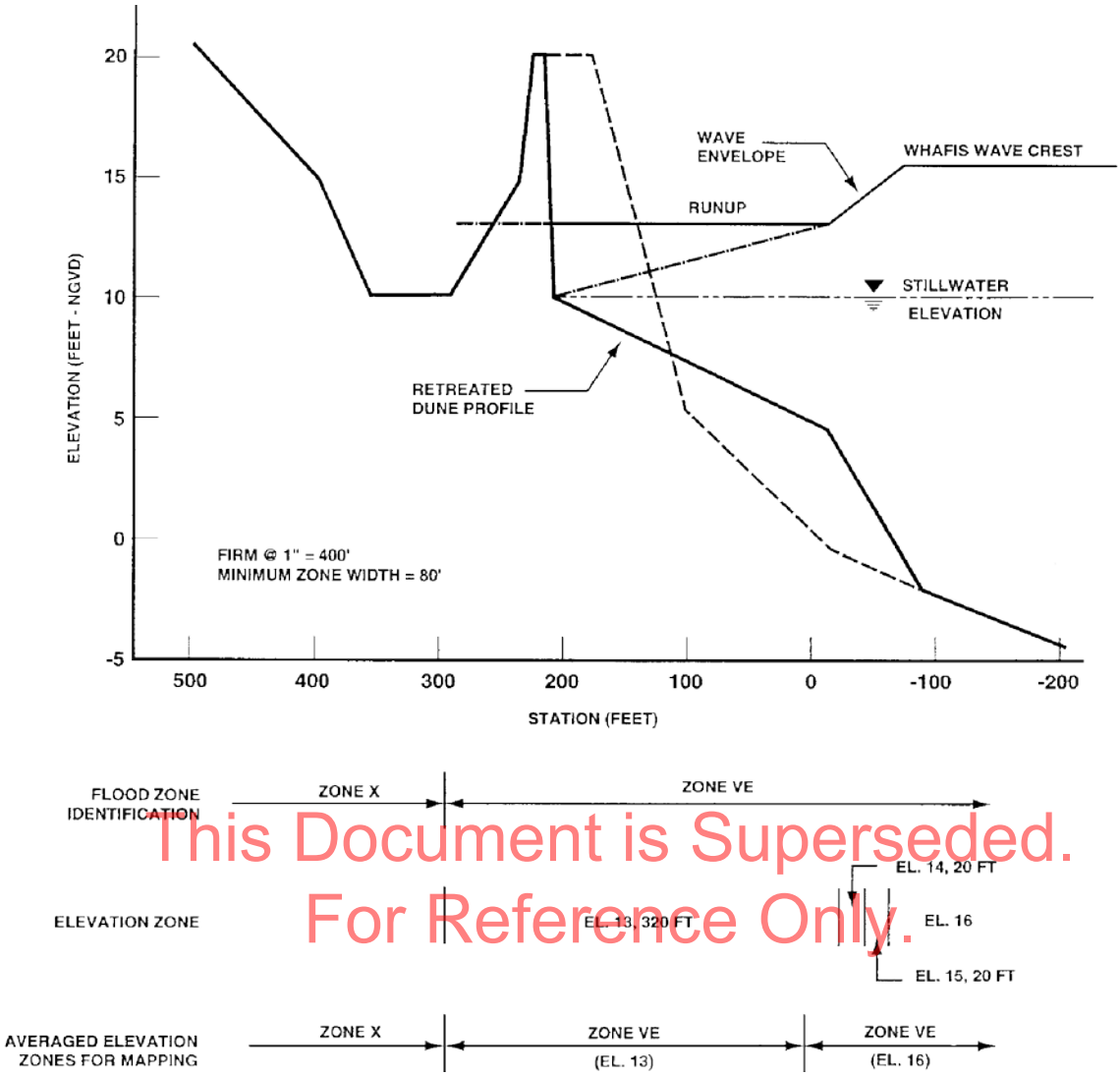


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**Figure D-28. Identification of Elevation Zones, Example 2: Duneface Retreat with Relatively High Remnant.**

Figure D-29 illustrates an example of a retreated duneface with a relatively small remnant having low relief. A mean runup elevation of 12 feet is calculated for the eroded profile, and this flood elevation is assigned through the dune, all of which is designated as Zone VE . The division into separate map zones is similar to the division in Figure D-28. Because the dune remnant extends less than 7 feet above the SWEL, appreciable wave overtopping is expected during the 1-percent-annual-chance flood. An area landward of the dune of about the minimum mapping width is designated as a Zone AO, depth 1 foot.

Figure D-30 illustrates an example of dune removal where there is some runup and overtopping of the remaining stub. As in Figure D-27, the VE Zone with a runup elevation of 11 feet is extended to the dune toe and the Zone VE, elevation 16 feet, is located just landward of the shoreline. Although elevation 14 feet is shown on Figure D-30 for the intermediate VE Zone, elevation 13 feet could also be used; adjacent transects should be examined and a compatible BFE should be selected. Also note that the boundary between the Zone AO, depth 1 foot, and the Zone AE, elevation 7 feet, is at the intersection of the SWEL and ground profile.

An eroded bluff is shown in Figure D-31. The angle of the bluff face remains the same while the seaward extension from the toe is a 1:40 slope. The computed runup elevation slightly exceeds the bluff crest and is higher than the maximum wave crest elevation. The area is designated Zone VE, elevation 18 feet, until the difference between the runup elevation and the ground is less than 3 feet. In this figure, the Zone AE, elevation 18 feet, is slightly narrower than the minimum mapping width. As was recommended for the example in Figure D-27, the neighboring area on the work map should be examined to determine if this zone should be mapped. AE Zones are usually not mapped for bluffs unless computed runup exceeds the bluff crest, as shown in Figure D-31. (Note: Figures D-16 and D-17 outline another flooding treatment of bluffs where computed runup is well above the crest.)

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On sandy shores, transects usually are extended across barrier islands, marshes, inland water bodies, etc., such that at least two VE Zones can be identified. Procedures in these cases are the same, with elevation averaging also very common. With a little practice, identification of the flood zones and elevations becomes fairly routine using the wave envelope and transect profile.

With shore structures having steep slopes, runup elevations are relatively high and a wide range of wave hazards can occur, including erosion or scour near the structure. These circumstances may result in a variety of distinct and compact situations, where appreciable engineering judgment can be required for appropriate assessment of flood hazards.

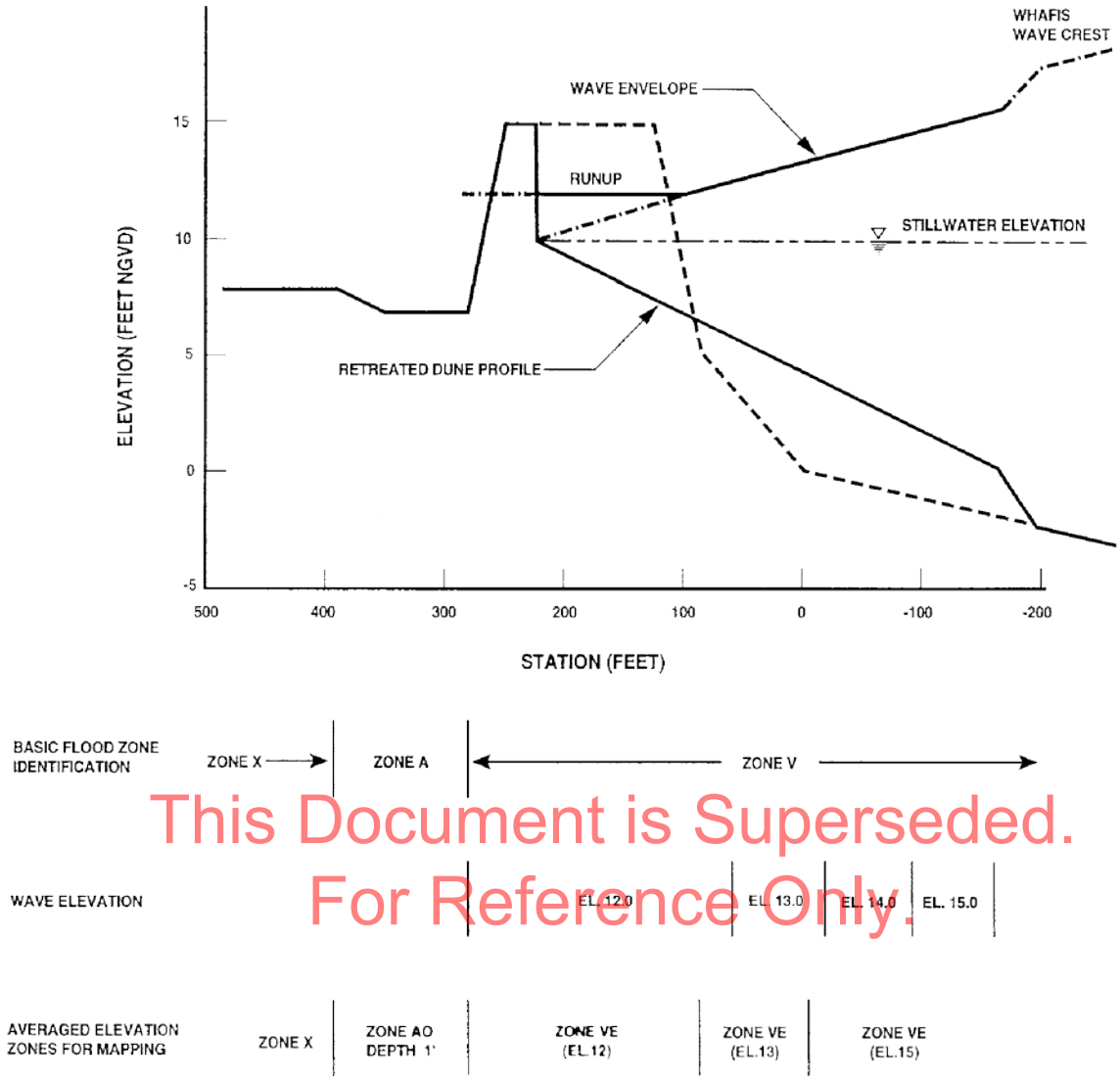


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**Figure D-29. Identification of Elevation Zones, Example 3: Low Retreated Dune with Wave Overtopping.**

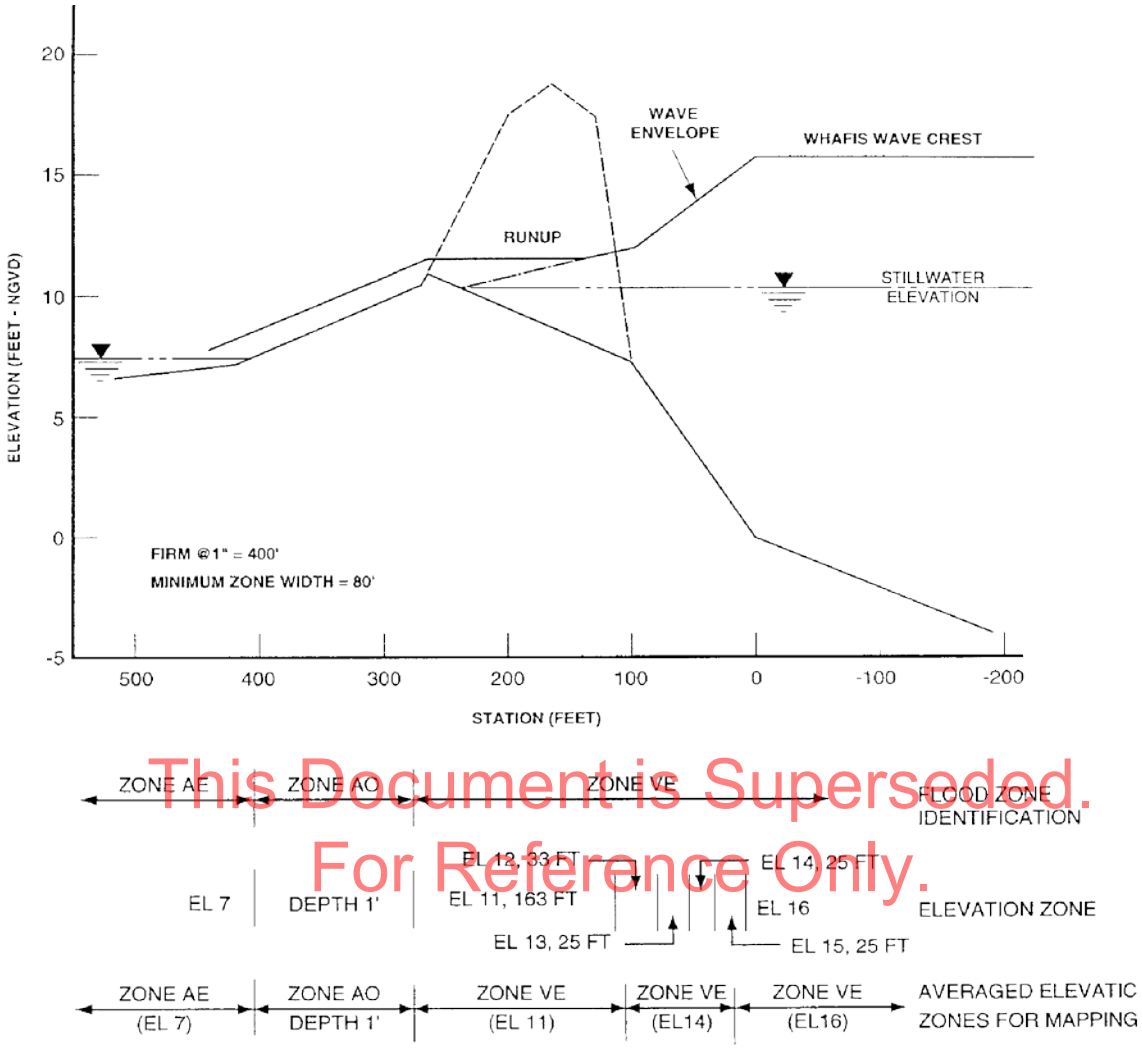


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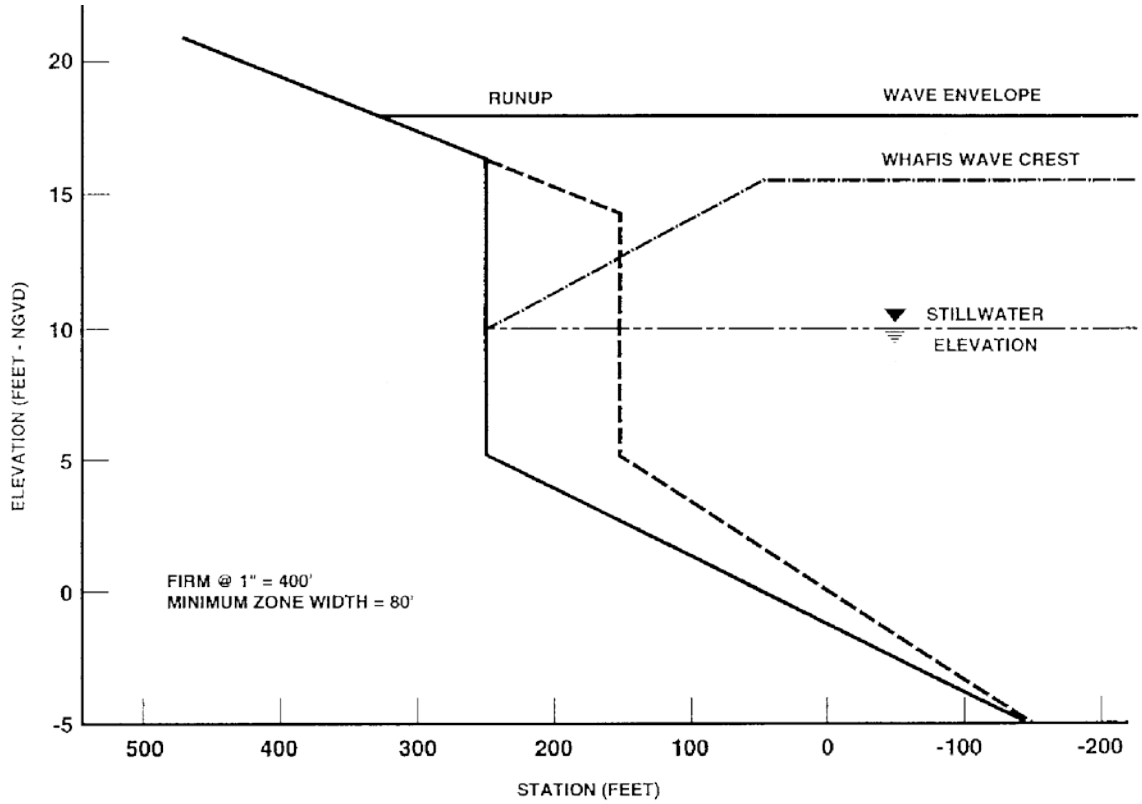
**Figure D-30. Identification of Elevation Zones, Example 4: Dune Removal with Wave Runup and Runoff**

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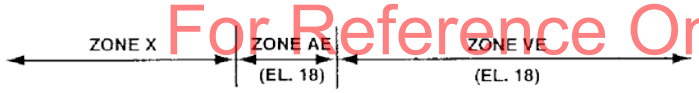


**Figure D-31. Identification of Elevation Zones, Example 5: Eroded Bluff with Wave Runup**

Figures D-32, D-33, and D-34. illustrate schematic effects for a few basic configurations, presuming the structures remain intact through the 1-percent-annual-chance flood and no appreciable shore erosion occurs

Figure D-32 illustrates an example of moderate structure overtopping expected for waves accompanying the 1-percent-annual-chance flood. The structure crest has sufficient freeboard above the 1-percent-annual-chance SWEL to contain a calculated mean runup of 6 feet, but extreme wave runups are likely to overtop the structure intermittently. The entire extent of shore structure is treated as a unit and designated as a VE Zone, and is assigned the mean runup elevation of 16 feet. Landward of the structure, an area with at least the minimum mapping width is appropriate for designation as Zone AO, depth 1 foot, with the extent of the zone depending on ground profile.

Figure D-33 illustrates an example of a structure extending above the 1-percent-annual-chance SWEL but heavily overtopped by wave action. The calculated mean runup elevation is 5 feet above the seaward face, but that is reduced to the maximum excess runup of 3 feet in assigning a flood elevation of 16 feet for the shorefront VE Zone. That zone extends through the entire structure and over an additional 30 feet landward, because likely wave impact area reaches beyond the structure during the 1-percent-annual-chance flood. Cumulative wave overtopping yields ponding within an additional landward area that is 100 feet wide, which is designated as Zone AO, depth 2 feet.

Figure D-34 illustrates an example of a structure covered by 3 feet of water during the 1-percent-annual-chance flood. Flood depth is not sufficient for waves 3 feet in height to propagate inland of the structure, but the V Zone must extend to 30 feet landward of the structure, in view of likely wave effects through the flood's course. The shore structure is too narrow for multiple V Zones to be delineated, so there is one designation of Zone VE, elevation 13 feet. Landward of that zone, further wave hazards occur in the Zone AE, elevation 11 feet.

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In examining Figures D-32, D-33, and D-34, it may seem surprising that relatively high structures can result in higher flood elevations, compared to an inundated structure. However, a structure with more freeboard can deflect incident wave action to greater elevations during the 1-percent-annual-chance flood, so the present zonations are physically appropriate. The hazard zonations landward of coastal structures generally have more importance, and they reflect the greater protection provided by higher but durable structures.

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### D.2.7.4 Mapping Procedures

Properly integrated delineation of the results of flooding analyses involves judgment and skill in reading topographic and land cover maps. The time and effort put forth to determine the flood elevations and extents will be negated if the results of these analyses are not properly delineated on the FIRM. The FIRM is usually produced from the work maps described in Subsection D.2.2. Therefore, the Mapping Partner shall transfer the flood zones and elevations identified on the transects to the work maps and interpolate boundaries between transects. The Mapping Partner shall set up the work maps with contour lines, buildings, structures, vegetation, and

transect lines clearly located. Because roads are often the only fixed physical features shown on the FIRM, the

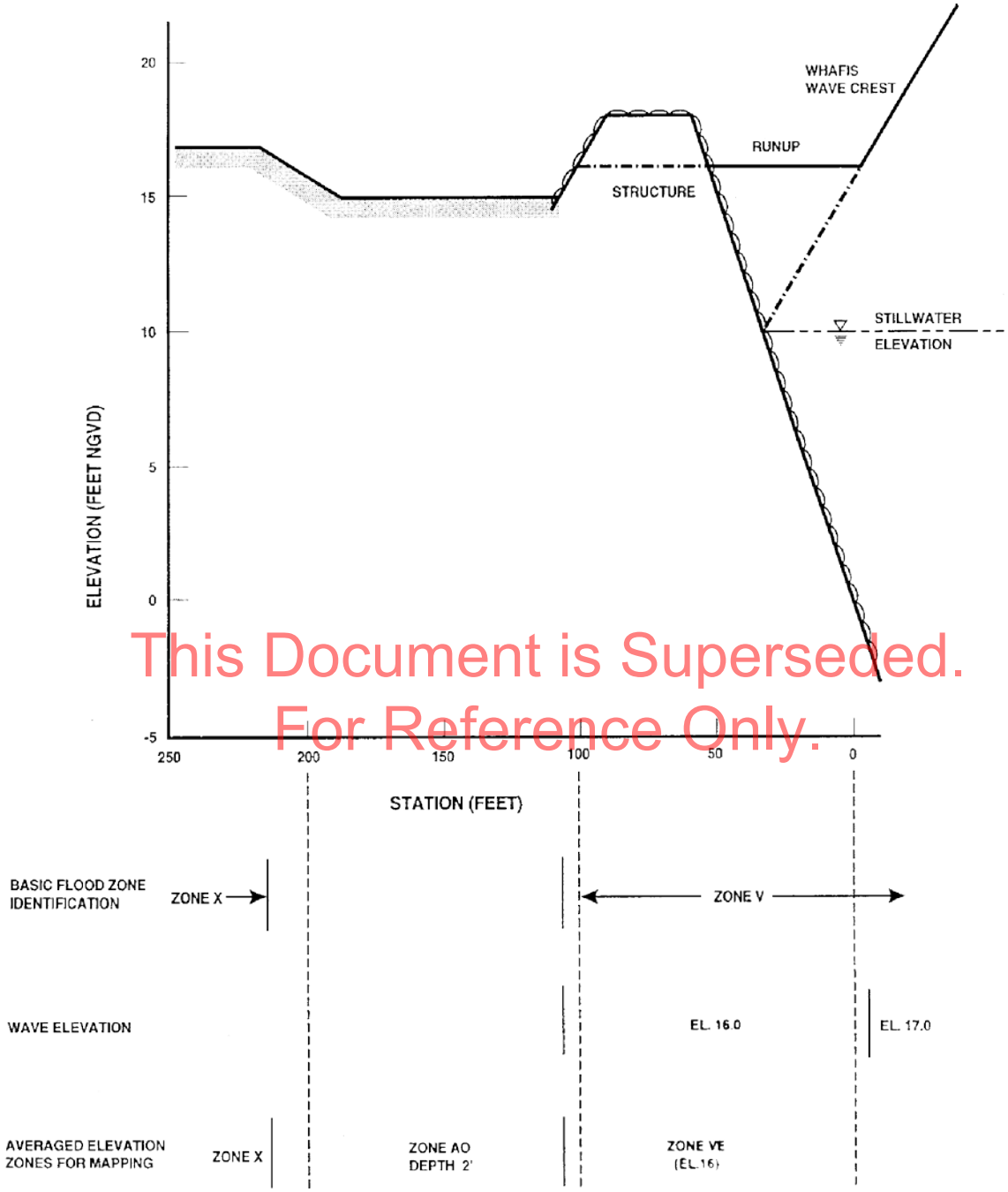


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**Figure D-32. Identification of Elevation Zones, Example 6: Coastal Structure with Moderate Wave Overtopping**

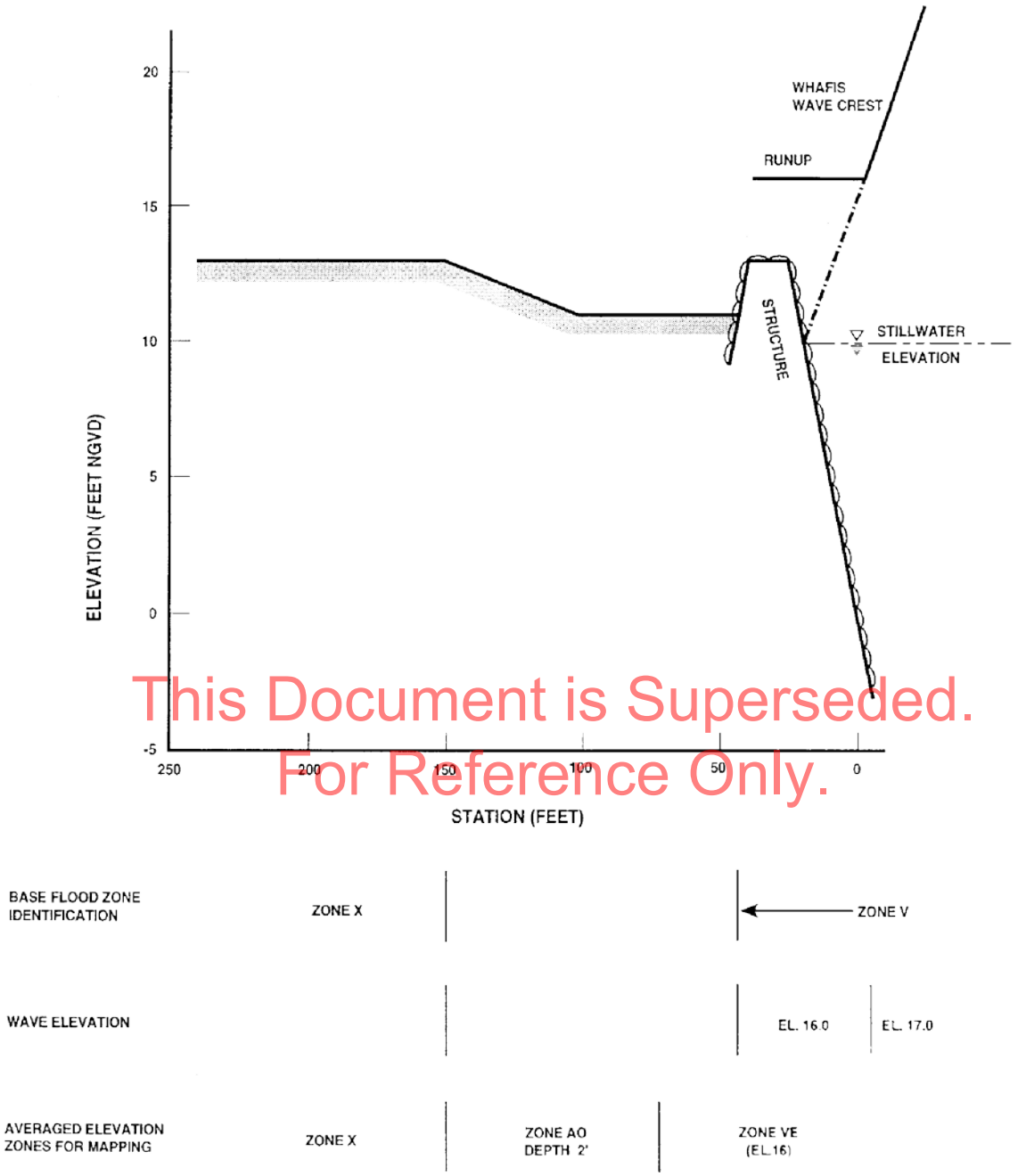


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**Figure D-33. Identification of Elevation Zones, Example 7: Coastal Structure with Severe Wave Overtopping**

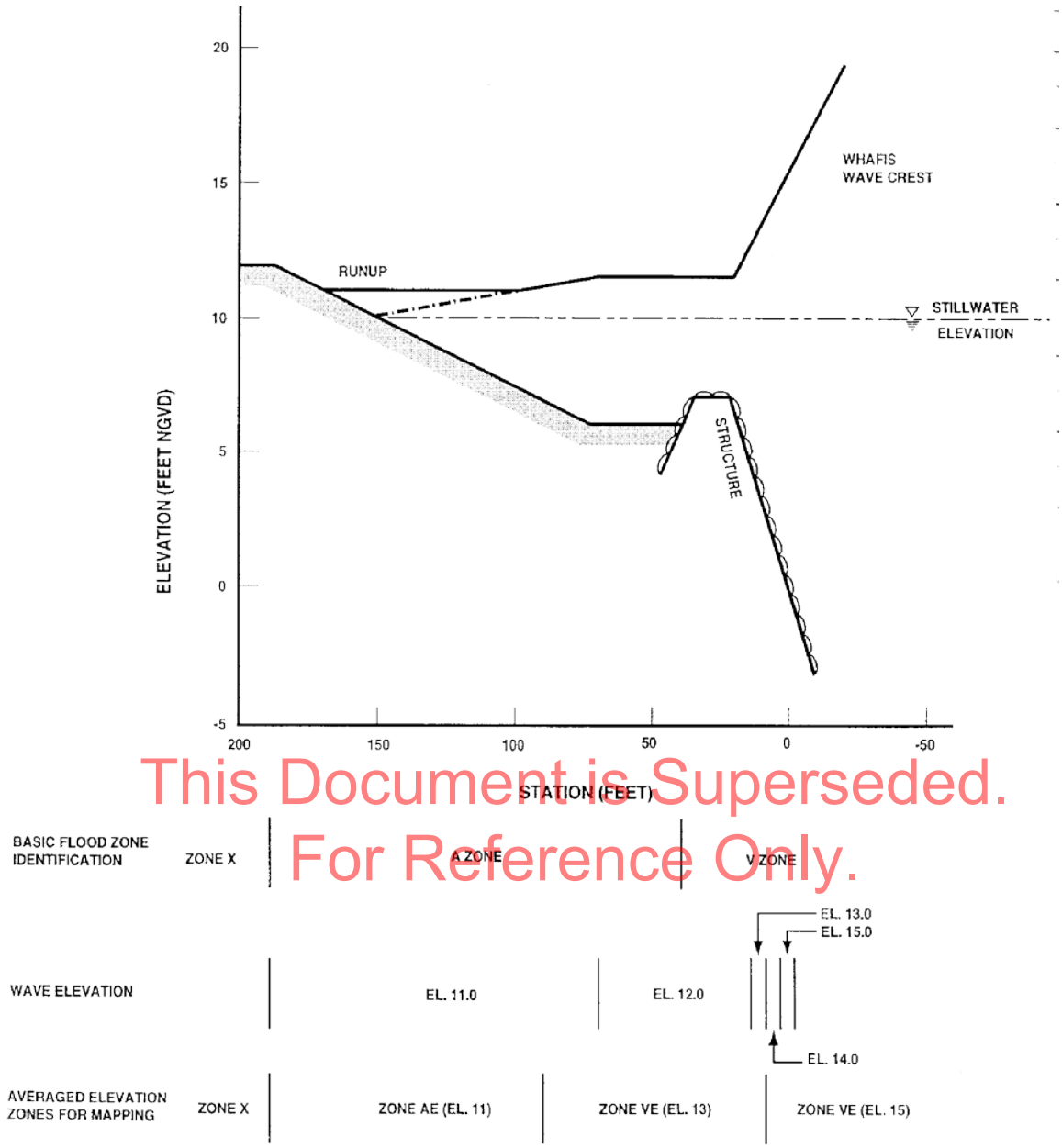


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**Figure D-34. Identification of Elevation Zones, Example 8: Coastal Structure with Inundation**

Mapping Partner shall ensure that other features and the flood zone boundaries are properly located on the work maps in relation to the centerline of the roads as they will appear on the FIRM.

For each transect, the Mapping Partner shall transfer the identified elevation zones from the transect to the work maps, marking the location of the boundaries along the transect line so that boundary lines can be interpolated between transects. The Mapping Partner shall ensure that boundaries are marked at the correct location. Because of erosion assumptions, the location of the elevation 0.0 shoreline changes on the transect but not the work maps.

Using the transect profile, the Mapping Partner shall determine the location of the zone change in relation to a physical feature (e.g., ground contour, back side of a row of houses, 50 feet into a vegetated area) and delineate the boundary line for the area represented by that transect along this feature. The Mapping Partner shall measure the widths of the zones carefully; zones that narrow to less than 0.2 inch must be tapered to an end. Likewise, if the zone becomes much wider, it may be possible to break an averaged elevation zone into two mapped elevation zones.

One of the more difficult steps in delineating coastal flood zones and elevations is the transition between transect areas. Good judgment and an understanding of typical flooding patterns are the best tools for this job. Initially, the Mapping Partner shall locate the area of transition (an area not exactly represented by either transect) on the work maps. The Mapping Partner shall then delineate the floodplain boundaries for each transect up to this area. The Mapping Partner shall examine how a transition can be made across this area to connect matching zones and still have the boundaries follow logical physical features. Other transects similar to this area could give an indication of flooding. Sometimes the elevation zones for the two contiguous transects are not the same; in such cases, the Mapping Partner may have to taper the zones to an end or enlarge the zones and subdivide them in the transition area.

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Communities with significant flooding hazards from wave runup may have one transect representing more than one area because the areas have similar shore slopes. In this case, the Mapping Partner shall identify the different areas and delineate the results of the typical transect in each area. Transition zones may be necessary between areas with high runup elevations to avoid large differences in BFEs and to smooth the change in flood boundaries. These zones are to be fairly short and cover the shore segment with a slope not exactly typical of either area. The Mapping Partner shall determine the transition elevation using judgment in examining runup transects with similar slopes. The Mapping Partner shall not use transition zones if there is a very abrupt change in topography, such as the end of a structure.

Lastly, Mapping Partner shall map the Zone X areas. The Mapping Partner shall show areas below the 0.2-percent annual chance SWEL that are not covered by any other flood zone as Zone X (shaded) on the FIRM. Often the maximum runup elevation is higher than the 0.2-percent-annual-chance SWEL; in such cases, the Zone X (shaded) designation will be used in that area. All other areas are designated Zone X without shading.

Because flood elevations are rounded to the nearest whole foot, the Mapping Partner does not need to spend hours resolving a minor elevation difference. Also, because structures or proposed structures must be located on the FIRM, the Mapping Partner shall attempt whenever possible to smooth the boundary lines and to follow a fixed feature such as a road. In preparing the FIRM,

the Mapping Partner shall ensure that the mapped results are technically correct and but the FIRM is easy for the local insurance agent, building inspector, or permit officer to use.

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## D.2.8 Required Documentation

The Mapping Partner shall fully document the coastal flood hazard determination for each affected community. Because FIS Reports and FIRMs form the basis of Federal, State, and local regulatory and statutory enforcement mechanisms and are subject to administrative appeal and litigation, Mapping Partners shall ensure that all technical processes and decisions are recorded and documented. The FIS Report may not contain all the documentation that would be needed for a response in the event that the study results are questioned. Therefore, the Mapping Partner shall prepare an engineering report for each study. This report will provide detailed data needed by FEMA or the community to reconstruct or defend the study results on technical grounds. The minimum information required for the engineering report is summarized below.

**Basic Data**.

In this section, the Mapping Partner shall include all contacts made to obtain data for the study. All basic data used must be fully referenced and, if possible, reproduced in the report. All historical flood information must be documented in this section, even if the Mapping Partner did not use the information in quantitative analyses.

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**Transects**

The Mapping Partner shall show all transects on a transect location map. Each transect must be plotted separately and show the erosion assessment, input data for wave models, wave envelope, and zone determination.

**Model Input and Output**

The Mapping Partner shall provide computer printout listings for input and output data for both the Wave Runup and Wave Height Models for all the transects. These listings must be keyed to the transect location map and transect plots.

**Study File**

During the course of the study, the Mapping Partner shall maintain a file containing records of all coordination, activities, and decisions. This is especially important where nonstandard approaches were used and engineering judgment played a significant role. The Mapping Partner shall ensure this file meets the requirements for a Technical Support Data Notebook as documented in Appendix M of these Guidelines.

[February 2002]

# D.3 Wave Elevation Determination and V Zone Mapping: Great Lakes

Methodologies for determining coastal flood elevations and flood insurance risk zones have been adopted and refined over a period of time, as recounted in Section D.2 and in FEMA's *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping* (1995). Standard treatments for U.S. seacoast sites address wave heights, wave crest elevations, wave runup, and coastal erosion accompanying the 1-percent-annual-chance flood (FEMA, 1995). The effects of such waves determine flood elevations and the extent of Coastal High Hazard Areas (V Zones).

Until recently, wave effects were not taken into account along Great Lakes shores, but storms during the high water levels from 1985 to 1987 prompted reconsideration of this omission. A USACE study in 1989 concluded that recent significant storm damage at New York, Michigan, and Illinois sites confirmed the importance of wave runup contributions to actual coastal flooding on the Great Lakes. That finding led to specific calculation procedures to determine runup elevations appropriate to Great Lakes coasts with barriers to wave propagation (FEMA, 1991). Later, the standard NFIP seacoast model for wave height analysis was modified to apply to the lower wind speeds typical of Great Lakes events, and a detailed review addressed wave conditions and coastal erosion processes and quantities accompanying extreme floods at various U.S. lake sites (Dewberry & Davis, 1995). All necessary guidance has now been developed for treating wave effects in communities located along the Great Lakes

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This subsection unifies the technical policies, procedures, and methodologies relevant to conducting a flood hazard study for a Great Lakes coastal community. In addressing coastal studies for specific geographical regions, these Guidelines and FEMA's *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping* (1995) serve as user guides. Appropriate application of this guidance, along with an understanding of coastal engineering principles, will assist Mapping Partners in determining coastal flooding elevations and hazards and presenting this information on the FIRM.

[February 2002]

## D.3.1 Appropriate Treatments

The methodologies that shall be used to treat all the wave hazards possibly associated with a 1-percent-annual-chance flood are summarized in Table D-14. However, Mapping Partners must recognize that not every wave effect that occurs on the Great Lakes must be addressed for every flood hazard study or for every lakeshore community. To minimize unnecessary effort, it is useful early in the study process to identify those wave effects that can contribute noticeably to the BFEs and thus should be analyzed. Whether or not a wave treatment is appropriate depends primarily on the basic type of coastal topography, as outlined in Table D-14.

**Table D-14. Important Wave Treatments for Typical Coastal Topographies**

| COASTAL TOPOGRAPHY | IMPORTANT WAVE TREATMENTS | | |
|---|---|---|---|
| | EROSION | RUNUP | WHAFIS |
| Rocky bluff | | x | x |
| Sediment bank or bluff | x | x | x |
| Sandy beach, small dunes | x | | x |
| Sandy beach, large dunes | x | x | x |
| Open wetlands | | | x |
| Shore protection structure | | x | x |

The objective of a coastal study is to provide legible and accurate flood hazard maps with appropriate BFEs including wave contributions. Although procedures to define V Zones are fully documented in these Guidelines, mapping V Zones may not be appropriate in some Great Lakes areas. Both engineering and practical judgment are required for a proper decision on this matter. The typical study finding is a narrow V Zone, making its usefulness uncertain on maps at usual scales. Also, relatively small numbers of existing coastal buildings are likely to be affected by possible V-Zone designations along some Great Lakes.

V Zones are to be mapped only when the Regional Project Officer (RPO) approves such action. Some common exceptions to required approval might include coastal areas lakeward of sizable bluffs or designated as primary frontal dunes, so that the V Zone can be clearly delineated.

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A flowchart with the basic study procedures for defining flood hazards in the Great Lakes region is presented in Figure D-35.

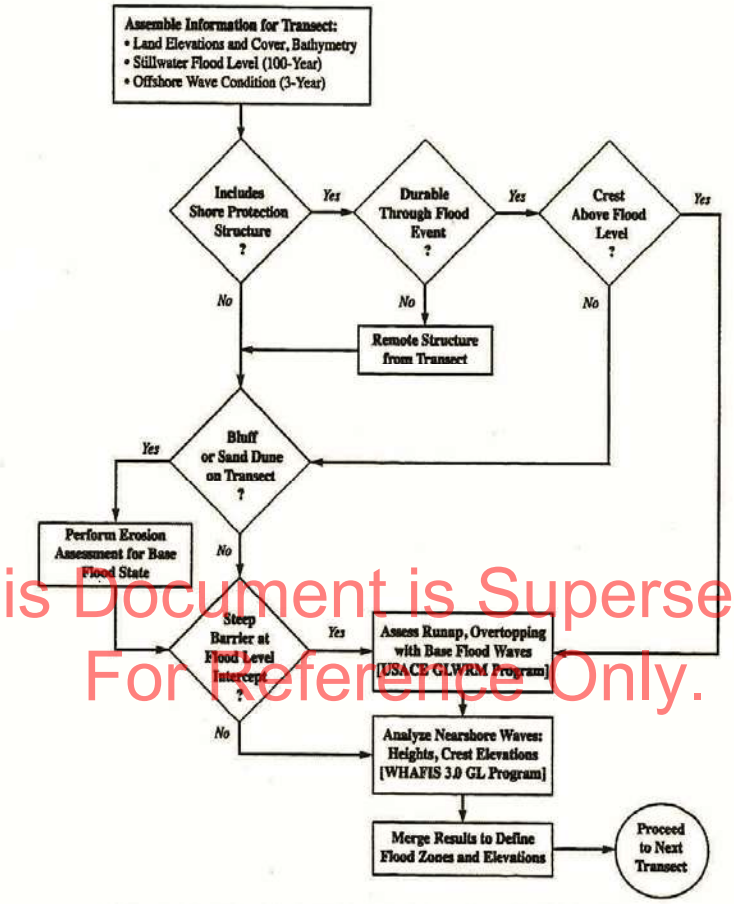


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**Figure D-35. Procedure for Defining Flood Hazards on Great Lakes Shores**

[February 2002]

## D.3.2 Data Requirements for Coastal Flood Hazard Analyses

A coastal flood hazard analysis begins with collecting the data and information required for the ensuing analyses, including the input needed for the computer models. The coastal models discussed here are executed along transects, which, as discussed earlier in this Appendix, are cross sections taken perpendicular to the mean shoreline to represent a segment of coast with similar characteristics. Thus, collected data are compiled primarily for use in developing transects and for locating and detailing the results on work maps. Work maps are to show the topography and land cover at a scale with sufficient detail to properly delineate the results of the analyses and interpolate between transects.

Data collection is to start at the community level and proceed with inquiries to appropriate county, State, and Federal agencies. To pursue any suggestions provided by government agencies, private firms specializing in topographic mapping or aerial photography may also be contacted.

This subsection describes the data requirements for coastal flood hazard analyses.

[February 2002]

### D.3.2.1 Stillwater Elevations

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The USACE's *Revised Report on Great Lakes Open-Coast Flood Levels* (1988) is FEMA's source for SWELs on the Great Lakes, at recurrence intervals of 10, 50, 100, and 500 years (reflecting 10-, 2-, 1-, and 0.2-percent-annual-chance flood elevations, respectively). Documented flood elevations pertain to specific U.S. reaches of open coast, defined as "lake shoreline which is unprotected by the presence of islands and which is uninterrupted by bays." These elevations are based on a standardized analysis of maximum annual water levels from long-term gage records (1900 to 1986) and are referenced to NGVD.

The USACE report on Great Lakes flood levels is divided into Phase I and Phase II reports. The Phase I report provides SWELs for most of the U.S. shoreline of Lake Superior (divided into five separate reaches), Lake Michigan (nine reaches), Lake Huron (eight reaches), Lake St. Clair (one reach), Lake Erie (24 reaches), and Lake Ontario (five reaches). In Subsection D.3.9, charts identifying separate reaches and the flood elevations on each lake are reproduced; except on Lake Erie, flood elevations usually remain constant over tens of miles along the shore. The Phase II report provides the flood levels for connecting channels and addresses general methods for developing flood levels in other areas, such as bays, inlets, and sheltered shorelines. For some of these areas, separate reports such as the "Saginaw Bay Flood Levels Report" for Lake Huron, have been prepared to document the SWELs (USACE, September 1989).

[February 2002]

### D.3.2.2 Transect Locations

Transects for coastal flood hazard analyses are to be located with careful consideration given to the physical and cultural characteristics of the land so that they will closely represent conditions in the vicinity of the transect. If they are carefully placed, excessive mapping interpolation of the BFEs between transects, as well as unnecessary study effort, can be avoided. The transects are to be placed more closely together in areas of complex topography, dense development, and unique flooding, and where computed wave heights and runup may be expected to vary significantly. Wider spacing may be appropriate in areas having more uniform characteristics. For example, a stretch of developed shoreline with various building densities, protective structures, and vegetation may require a transect every 1,000 feet or so, whereas a long stretch of undeveloped shoreline with a continuous dune or bluff of fairly constant height and shape, and similar landward features may require a transect only every 1 to 2 miles.

In areas where runup is significant, the location of transects is governed by variations in shore slope or steepness. In other areas where dissipation of wave heights is significant to the computation of flood hazards, transect location is based on variations in land cover, such as buildings and vegetation. Often, areas with similar characteristics may be scattered throughout a community, and the results from one transect are also representative of other locations and can be delineated accordingly.

The Mapping Partner performing the coastal flood hazard study shall locate transects on the work map to be submitted with the analysis, and shall compile the input data and displayed the data on individual profiles for each transect. The Mapping Partner shall take the data (e.g., topography, development, vegetation) not only at the transect site, but for the entire area or length of shoreline represented by the transect so that the input data depict average characteristics of the area. The Mapping Partner may divide the work map into transect areas to help in compiling the data.

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### D.3.2.3 Topographic Data

Topographic data must have a contour interval of equal or greater detail than that used for the effective FIS, and a minimum interval of 5 feet or 1.5 meters. While more detailed information, such as spot elevations or a smaller contour interval, can be useful in defining the dune or bluff profile and in delineating floodplain boundaries, it is required only when a map revision request with new coastal analyses is based on new detailed topographic data. As discussed in Volume 2, the data, usually in the form of maps, shall be certified and shall reflect current conditions in the area of the analysis or, at a minimum, conditions at a time more recent than the topographic data used in the effective FIS.

Topography must extend lakeward at least to the Low Water Datum defined for each Great Lake, as listed in Table D-14. The Low Water Datum corresponds to extremely low annual means of lake level during the 1900s and is described in terms of the International Great Lakes Datum of

1985 (IGLD85). The relation of NGVD29 to IGLD85 needs to be defined for each coastal flood hazard analysis site. NGVD29 is required as the datum for the topographic map.

If possible, the Mapping Partner shall check the shore topography to note any changes caused by construction, erosion, or other causes and document any significant erosion by location with descriptions, drawings, and/or photographs. The Mapping Partner is not required to field survey transects unless available topographic data are unsuitable or incomplete.

The community, county, and state are usually the best sources for topographic data. The Mapping Partner shall examine USGS 7.5-minute series topographic maps. The USGS maps may have a 5-foot contour interval, and if not, they are still often useful as a reference for planimetric features in the study area.

**Table D-14. Elevations of Low Water Datum on the Great Lakes**

| LOCATION | LOW WATER DATUM ELEVATION: | |
|---|---|---|
| | FEET ABOVE IGLD85 | FEET ABOVE NGVD29 (APPROXIMATE) |
| Lake Superior | 601.1 | 601 |
| Lake Michigan | 577.5 | 578 |
| Lake Huron | 577.5 | 578 |
| Lake St. Clair | 572.3 | 573 |
| Lake Erie | 569.2 | 570 |
| Lake Ontario | 243.3 | 244 |

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### D.3.2.4 Land-Cover Data

The land-cover data include information on structures and vegetation. Stereoscopic aerial photographs can provide the required data on structures and some of the data on vegetation. The aerial photographs must not be more than 5 years old unless they are updated by surveys. A local, county, or State agency may have the coastline photographed on a periodic basis. That agency may provide the photographs or give permission to obtain them from its contractor. Because topographic maps are often developed from aerial photographs, the Mapping Partner also shall contact the mapping contractor for the topographic maps for data.

Aerial photographs can provide the required data on tree- and bush-type vegetation and can be used to identify areas although not the specific type of grass-like vegetation. National Wetland Inventory maps from the U.S. Fish and Wildlife Service and color infrared aerial photographs can provide more specific data required for marsh plants. Ground-level photographs and surveys also are useful in providing information on the plants (e.g., density, species). State offices of coastal zone management, park and wildlife management, and/or natural resources should be able to provide information on significant vegetation types. Also, the Mapping Partner shall contact local universities with coastal studies and/or Sea Grant programs. The Mapping Partner

may conduct field surveys in lieu of the above sources, but these are more cost effective when used only to verify some of the data obtained from these sources.

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### D.3.2.5 Bathymetric Data

It is not possible to provide precise guidance on the extent of bathymetry needed for a Great Lakes FIS. In some cases, only typical water depths in the vicinity of shore structures will be required in the analysis of wave effects. For sand beaches, bathymetry out to water depths of approximately 30 feet is required for wave treatments. Bathymetry further offshore may be useful for interpreting likely differences between nearshore and offshore wave conditions. (See Subsection D.3.2.6). An advisable procedure for studies of Great Lakes sites is to gather any readily available bathymetric data, but to defer all data reduction or analysis until the need is firmly established. Bathymetric data can be acquired from National Ocean Survey nautical charts, although any reliable source can be used.

[February 2002]

### D.3.2.6 Offshore Wave Characteristics

One basic assumption in conducting coastal wave analyses is that wave direction must have some onshore component, so wave hazards occur coincidentally with the 1-percent-annual-chance flood. That assumption appears generally appropriate on open coasts and bay shores of the Great Lakes, where the 1-percent-annual-chance SWEL must include some contribution from storm surge and usually requires an onshore wind component. However, the assumption of onshore waves along the shores of connecting channels, near inlets, and behind protective islands may require detailed examination.

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Once the Mapping Partner has confirmed that sizable waves travel onshore during the 1-percent-annual-chance flood, the most important specification is wave period rather than wave height. This is because wave heights are severely limited by shallow water at sites where the models described in Subsections D.3.5 and D.3.6 are applied. Wave treatments within those models provide depth-limited wave heights controlled by the wave period, so that the specified period influences the results of coastal wave analyses. The specified wave period can pertain to offshore storm waves in deep water, because dominant or spectral peak period is commonly unchanged during complex wave transformations near the shore. The most notable sources of suitable storm-wave information along Great Lakes coasts are the USACE Coastal Engineering Research Center (CERC) Wave Information Studies (WIS) Nos. 22, 23, 24, 25, and 26, with one report for each Great Lake on computed wave conditions in deep water from 1956 to 1987 (Driver, Reinhard, & Hubertz, 1991 and 1992; Hubertz, Driver, & Reinhard, 1991; Reinhard, Driver, & Hubertz, 1991). Maps locating approximately 300 sites for which computed wave information is available, one map for each lake, are included in Subsection D.3.9.

The draft of "Basic Analyses of Wave Action and Erosion with Extreme Floods on Great Lakes Shores" (Dewberry & Davis, 1995) concluded from historical evidence that extreme floods were

usually accompanied by the local 1/2-year wave condition on Lake Ontario, or by the 3-year wave condition on Lakes Erie, Huron, Michigan, and Superior. Those wave heights can be determined using the simple treatment illustrated by Figure D-36. Tabulated significant wave heights in the CERC WIS reports include the extremes for each month/year at every calculation site, and the median of each set of results gives the 2-month/2-year wave height. Extreme wave heights at various recurrence intervals usually are well approximated by an exponential distribution, so those two known values on a semi-logarithmic graph define other significant wave conditions of interest, as demonstrated in Figure D-36.

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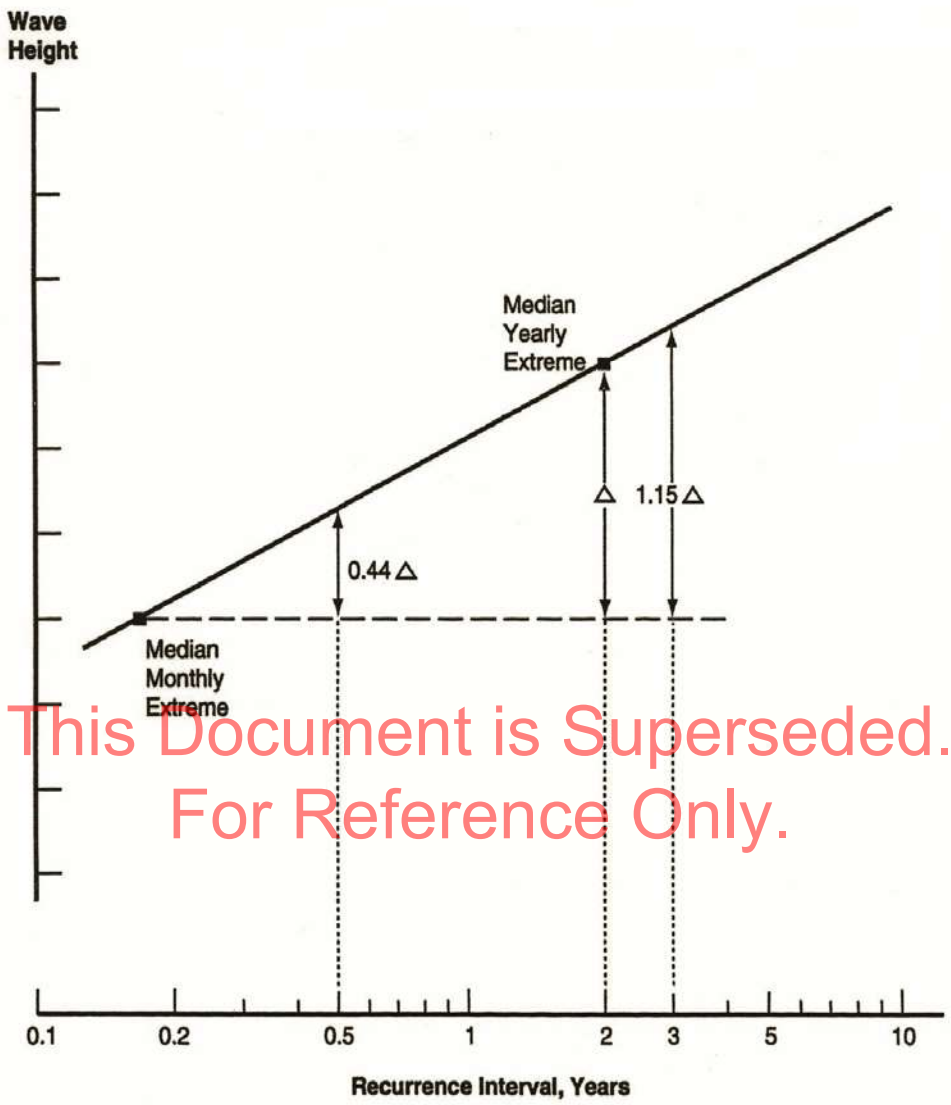


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**Figure D-36. Defining ½ Year or 3-Year Wave Height in an Exponential Distribution Using a Semi-Logarithmic Graph.**

Once a suitable offshore wave height is specified from the CERC WIS reports, the Mapping Partner shall determine the wave period crucial to coastal analyses in one of two ways. The more rigorous determination examines the electronic file of calculated conditions for 1956 to 1987, extracting cases with the specified wave height and with wave direction toward shore; prevalent wave period in those cases should be appropriate to the flood. Section D.3.9 includes examples of appropriate wave conditions derived for several sites on each of the Great Lakes. An alternative procedure considers wave steepness, or ratio of wave height to wavelength, with these typical values for storm waves: 0.035 for Lake Ontario or Lake Erie, 0.04 for Lake Huron or Lake Michigan, and 0.045 for Lake Superior. In deep water, the wavelength is 0.16 times the gravitational acceleration times the wave period squared, so specified wave steepness and wave height imply a suitable wave period for the site.

The hindcast wave study of the CERC WIS reports provides no information for Lake St. Clair, or within major embayments and connecting channels of the Great Lakes. Such sites require an independent assessment to define likely wave characteristics associated with the 1-percent-annual-chance flood. Fundamental information for such an assessment includes the water basin geometry at a site and the meteorology of storms potentially yielding the 1-percent-annual-chance SWEL, i.e., capable of generating the surge magnitude needed in addition to a high mean lake level.

Major factors in wave generation are windspeed and duration, local water depth, and fetch length. Fetch length is the over-water distance along which waves arise (USACE, 1984). In the Great Lakes vicinity, a windspeed of 40 mph sustained for several hours is usually appropriate to the 1-percent-annual-chance flood. For some cases, fetch length might be estimated as straight-line distance in the wind direction, but current guidance specified in the USACE ACES manual (USACE, 1992) pertinent to many Great Lakes sites indicates that a more involved analysis of restricted fetches must be performed for water basins of relatively complex geometry. The effective fetch length is derived as a weighted average of available distance with angle from the wind direction, as outlined in Figure D-37. A PC-compatible computer program included with the ACES manual is convenient for evaluating restricted fetch geometries and provides estimates of representative wave height and wave period based upon recommendations by CERC on wave generation.

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### D.3.2.7 Coastal Structures

Documentation gathered for each coastal structure that may provide protection from 1-percent-annual-chance flood hazards should include the following:

- Type and basic layout of structure;
- Dominant site particulars (e.g., local water depth, structure freeboard, ice climate); etc.
- Construction materials and present integrity;

•

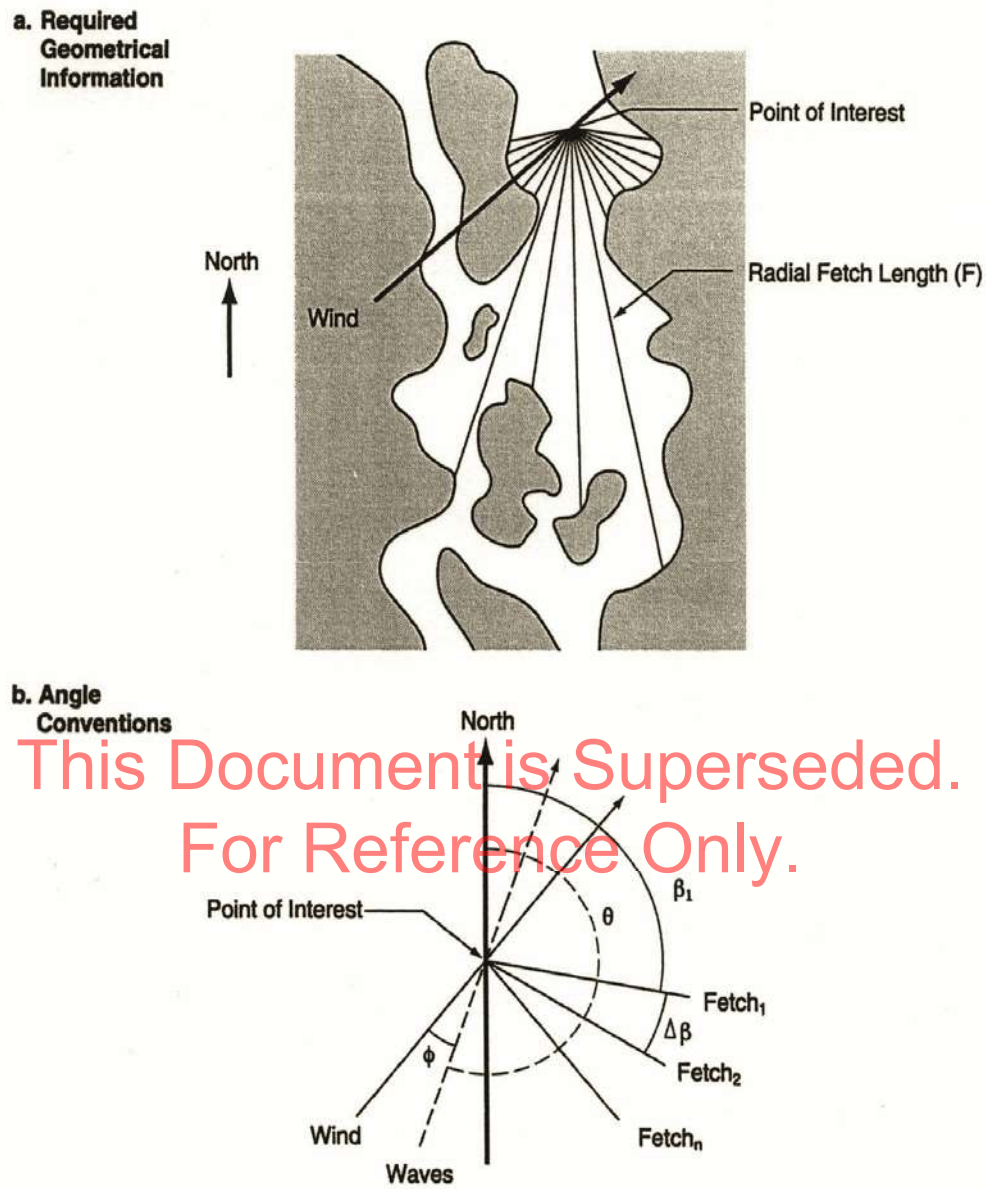


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**Figure D-37. Outline of Geometry for Wave Development on Restricted Fetches, from ACES Direction of Wave Development (θ) is Defined by Maximizing the Product $[(F_\phi)^{0.25} \cdot (\cos \phi)^{0.44}]$.**

- Historical record for structure, including construction date, maintenance plan, responsible party, and repairs after storm episodes; and
- Clear indications of effectiveness/ineffectiveness.

The Mapping Partner may develop much of this information through office activity, including a careful review of aerial photographs. In some cases of major coastal structures, site inspection could be advisable to confirm preliminary judgments.

[February 2002]

### D.3.2.8 Historical Erosion Accounts

Coastal erosion can occur during any major storm; however, the most significant erosion events for the purpose of a coastal FIS are those that occur with major storms during historical periods of high lake levels. Ideal information documenting storm-eroded cross sections will seldom be available because studies including repetitively surveyed profiles appear rare, except at some Lake Michigan sites. Although quantitative data may not be available, qualitative information can be valuable in confirming that reasonable results are obtained from the erosion assessment. The Mapping Partner shall conduct a search for erosion descriptions in newspaper articles or other publications, focusing on recent intervals of high mean lake levels. In addition, State agencies may be able to provide long-term recession rates over the study area. These are helpful in demonstrating local susceptibilities to storm-induced erosion.

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### D.3.2.9 Historical Flood Information

Information from previous storms and floods can be valuable in developing proper assessments of coastal flood hazards. This is particularly true on the Great Lakes, because many notably extreme events occurred on the four western lakes during 1985, 1986, and 1987 and ample information should be readily available for many study sites.

General descriptions of flooding are useful in determining what areas are subject to flooding and in obtaining an understanding of flooding patterns. More specific information, such as erosion associated with the event or the location of buildings damaged by wave action, can be used to verify the results of the coastal analyses. When quantitative data on the effects, recorded water elevations, and offshore wave conditions are available, the Mapping Partner shall check those data for proximity to the coastal site and impact on the evaluation. Those data can be used to estimate recurrence intervals for SWEL and wave action during the event and assist in the appropriate comparison to the 1-percent-annual-chance flood conditions and SWELs established by the USACE for the specific recurrence intervals (1988).

Local, county, and State agencies are usually good sources for historical data, especially during the more recent events. It is becoming common practice for these agencies to record significant

flooding with photographs, maps, and/or surveys. Federal agencies such as the USACE, USGS, and NRC prepare post-storm reports for the more severe storms. Local libraries, newspapers, and historical societies may also be able to provide some useful data.

Additional criteria and submittal requirements for historical information are identified in the certification forms package for Study Contractors (SC-1) and the application/certification forms package (MT-2) for map revision requests.

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## D.3.3 Evaluation of Coastal Structures

The crucial first consideration in evaluating a coastal structure is whether it was properly designed and has been maintained to provide protection during the 1-percent-annual-chance flood. If it can be expected to survive the 1-percent-annual-chance flood, the structure should figure in all ensuing analyses of wave effects (erosion, runup, and wave height). Otherwise, it should be considered destroyed before the 1-percent-annual-chance flood and removed from subsequent transect representations.

The USACE technical report entitled *Criteria for Evaluating Coastal Flood-Protection Structures* (Walton, Ahrens, Truitt, & Dean, 1989) recommends specific criteria for evaluating coastal flood-protection structures in regard to the 1-percent-annual-chance flood. A FEMA memorandum dated April 23, 1990, entitled "Criteria for Evaluating Coastal Flood Protection Structures for National Flood Insurance Program Purposes," based on the USACE report, provides a self-contained account of the evaluation process. The criteria in the memorandum have been adopted as the basis for NFIP accreditation of new or proposed coastal structures to reduce the flood hazard areas and elevations designated on the current NFIP maps. Ideally, these evaluation criteria could be applied to existing coastal structures, but for older structures, design and construction information sufficient to complete the formal evaluation is typically unavailable. For these structures, engineering judgment based on visual inspection and any historical evidence should be used.

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In general, for evaluation of coastal structures on the Great Lakes the Mapping Partner shall rely on engineering judgment firmly based on experience regarding structural stability at sites with similar flood and wave climate. Because extreme floods have been relatively common over the past decade on the Great Lakes, the Mapping Partner shall consider historical information about a particular structure in its evaluation. Construction date and damage history of a structure permit a performance record to be accumulated for events potentially comparable to the 1-percent-annual-chance flood.

Analysis based on historical information and past performance may be complicated by one unique aspect of Great Lakes design considerations. The 1990 FEMA memorandum specifies that representative analyses be carried out at a range of water levels, usually from the Low Water Datum to the 1-percent-annual-chance SWEL for Great Lakes sites. However, incident wave conditions associated with the 1-percent-annual-chance flood may be markedly less extreme than those expected for lower but more persistent water levels near long-term Mean Lake Level.

Nevertheless, even where water depth at the structure site strongly limits local wave heights, the most severe conditions for design could still occur during the 1-percent-annual-chance flood; therefore, the Mapping Partner must consider these conditions.

The USACE technical report identifies the four primary functional types of coastal flood protection structures: gravity seawalls, pile-supported seawalls, anchored bulkheads, and dikes or levees. The report recommends as a general policy that "FEMA not consider anchored bulkheads for flood-protection credit because of extensive failures of anchored bulkheads during large storms" (p. 100). However, the report provides no examples for the Great Lakes. Seacoast storm conditions are possibly quite different from the 1-percent-annual-chance flood on the Great Lakes; therefore, this structure type cannot be completely discredited.

The FEMA memorandum focuses on structures designed for flood protection. Such structures can have a significant impact on the information shown on a FIRM, perhaps directly justifying the removal of sizable areas from the Coastal High Hazard Area. However, structures in other categories also are to be considered. Although a breakwater may act primarily to limit wave action, and a revetment primarily to control shore erosion, these structures also can provide 1-percent-annual-chance flood protection. The FEMA memorandum places the responsibility on local interests to certify new structures; however, it is crucial that the Mapping Partner evaluate the structure accurately and consider its effects. For example, a structure might decrease flood impacts in one area, yet increase erosion or wave hazards at adjacent sites. Of course, the greater the potential effects of a coastal structure, the more detailed the evaluation process should be.

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As discussed in Volume 2, additional requirements regarding coastal structures are included on Form 10 of the Application/Certification forms package (MT-2) for map revision requesters.

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## D.3.4 Erosion Assessment

Along many Great Lakes shores, erosion accompanying the 1-percent-annual-chance flood may change the location and alter the form of an existing sedimentary barrier extending above the local 1-percent-annual-chance SWEL. Mapping Partners must assess the likely erosion before proceeding to determination of additional flood effects dependent on topography, such as wave runup or overtopping, or overland wave heights. Procedures described here are meant to give schematic estimates of eroded transect geometry suitable for the purposes of a coastal FIS or map revision request on the Great Lakes.

In an erosion assessment relating to the 1-percent-annual-chance flood, Great Lakes coasts may be separated into three basic site categories:

1. Sandy shores with backing dunes or banks;

2. Backshore bluffs of cohesive material; and

3. Other shore situations more resistant to erosion during extreme floods, with bedrock, wetlands, shore protection, and other conditions.

For the third category, erosion is usually not too important a consideration, so the major distinction for present purposes is between sand dunes and cohesive bluffs. Besides up-to-date coastal topography, information about the basic shore type is crucial for an appropriate erosion assessment pertaining to the 1-percent-annual-chance flood. Also, documented erosion effects during a historical flood at the study site can be useful in a valid assessment of 1-percent-annual-chance flood effects, but such evidence requires careful interpretation, as discussed below.

Detailed examination of recent record episodes of lake levels (Dewberry & Davis, 1995) provides several notable findings:

- Extreme Great Lakes floods usually involve rather moderate storms during relatively brief intervals when mean lake level is significantly higher than the long-term average.

- The storm situation for an extreme flood on Lake Ontario is markedly different than on Lake Erie, Lake Huron, Lake Michigan, Lake Superior.

- Coastal erosion on the Great Lakes exhibits extreme geographical and temporal variability during intervals of high mean lake level.

Quantitative analysis establishes that Great Lakes erosion cross sections expected during the 1-percent-annual-chance flood are 270 square feet on Lake Erie, Lake Huron, Lake Michigan, and Lake Superior and 190 square feet on Lake Ontario.

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These amounts refer to the flood episode alone and lie entirely above the local 1-percent-annual-chance SWEL. The stated results derive from Great Lakes verification of an analysis similar to that which was performed for Atlantic Ocean and Gulf of Mexico regions for the 540-square-feet erosion cross section in seacoast 1-percent-annual-chance floods. Appropriate application of this erosion guidance can depend on basic type of shore morphology, as illustrated in Figures D-38 (bluff) and D-39 (sand dune).

The cases consider no shore features lakeward of the basic flood barrier, because any distinct topography presumably will be removed by storm erosion before the peak effects to be considered. For the bluff case in Figure D-38, erosion projection is based on a retreated profile parallel to the existing bluff, but with a potential adjustment to the eroded face governed by soil stability considerations for the site. For the dune case in Figure D-39, erosion projection makes use of an escarpment slope of 45°, corresponding to the usual duneface geometry for storm conditions. In each case, the barrier is presumed to be appreciably more sizable than the specified erosion cross section, even though that usually is more appropriate for bluff erosion where the barrier in effect is unlimited. Erosion analysis may be unnecessary for very large coastal dunes, extending 20 feet or more above the SWEL; such sand accumulations may be considered resistant to notable storm erosion and to wave overtopping on the Great Lakes.

These quite simplified depictions of eroded profile geometry for Great Lakes shores may require modification in accordance with site-specific factors, engineering judgment, or the more detailed erosion considerations usually appropriate on seacoasts (FEMA, 1995). Comparison of present assessment results to historical effects for notable local floods must recognize the extreme variability evident in Great Lakes shore erosion during a given storm. Documented large or small amounts of erosion during a notable historical storm or flood at a particular Great Lakes site do not imply that similar effects should be expected for the 1-percent-annual-chance

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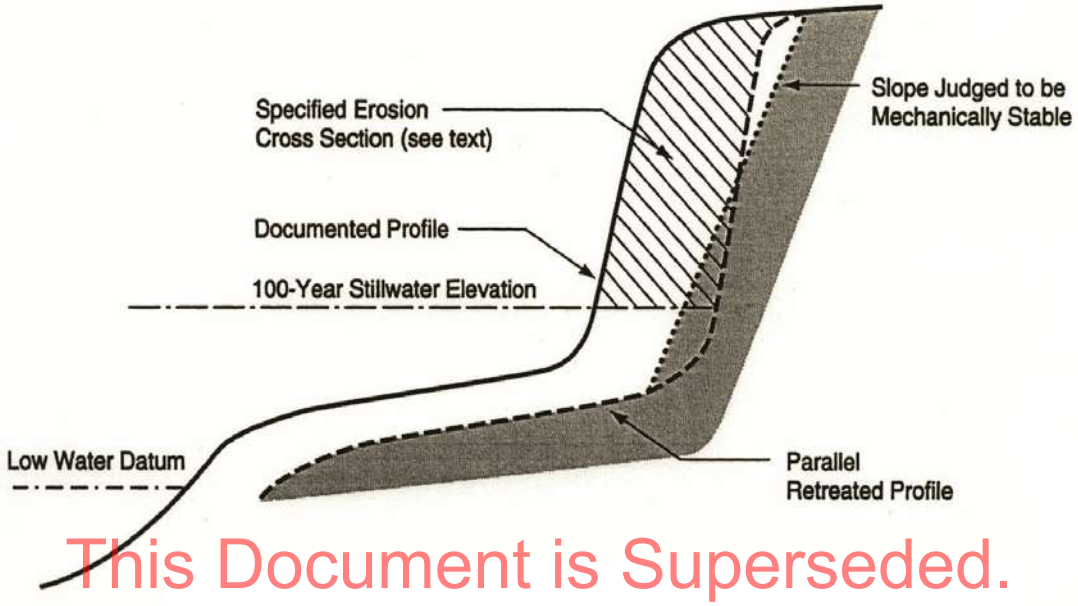


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**Figure D-38. Basic Erosion Considerations for Coastal Bluff Provides Shaded Shore Profile for Great Lakes Base Flood.**

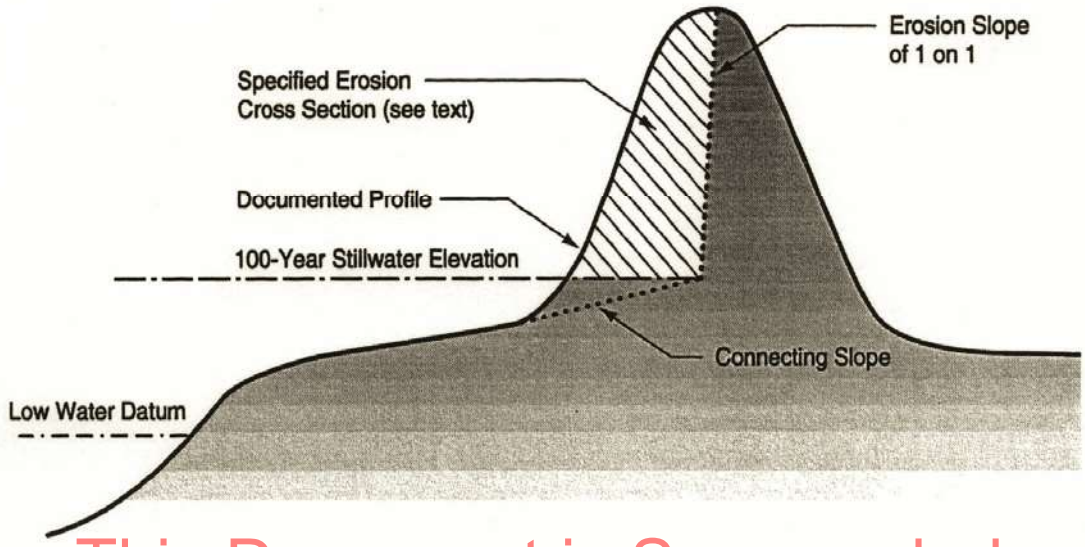


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**Figure D-39. Basic Erosion Considerations for Coastal Sand Dune Provides Shaded Shore Profile for Great Lakes Base Flood.**

flood. The only appropriate conclusion to be based directly on historical effects is that if a Great Lakes site has experienced no erosion over the past ten years, one should not assume that erosion will accompany the 1-percent-annual-chance flood.

The present evaluation guidelines outlined in Figures D-38 and D-39 lead to appropriate flood hazard identification, given that sizable wave effects on Great Lakes shores seldom penetrate inland past an erodible flood barrier in accordance with the geometrical consideration outlined in Figure D-40. In a Great Lakes FIS, the major result of an erosion assessment is a barrier profile both convenient and appropriate for ensuing wave analyses.

[February 2002]

## D.3.5 Wave Runup and Overtopping

Wave runup and overtopping constitute coastal hazards beyond those associated with stillwater coastal flooding and incident wave geometry. Wave runup is the uprush of water on a shore barrier intercepting the stillwater level. The water wedge both thins and slows during its excursion up the barrier, as residual momentum from wave motion near the shore is fully dissipated. The most significant characteristic of this process for present purposes is wave runup elevation: the vertical height above stillwater level ultimately attained by the extremity of uprushing water. Likely runup must be assessed for wave conditions expected to accompany the 1-percent-annual-chance flood. The extent of runup can vary greatly from wave to wave in storm conditions, so that a wide distribution of wave runup elevations provides the precise description of a specific situation. Wave overtopping occurs when an individual runup impulse surpasses the barrier crest and flood water penetrates inland of the shore barrier, perhaps with wave-like effects or with ponding of the flood waters behind the barrier.

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Current NFIP policy is that the mean runup elevation (rather than some occasional extreme) for a situation is appropriate in mapping coastal hazards of the 1-percent-annual-chance flood. The FEMA Great Lakes Wave Runup Model (GLWRM), which is based on methodologies recommended by the USACE, Detroit District, can be used to compute the mean runup elevation, as discussed in Subsection D.3.5.1. Although the GLWRM provides an entirely suitable runup elevation, it can treat only the three types of shore situation judged to be most frequently encountered on the Great Lakes. Therefore, adjustment or modification to computed results may be needed in applications at some sites. Section D.3.5.2 introduces some methods for extending the applicability of the GLWRM and also discusses other considerations potentially important for a Great Lakes coastal flood hazard evaluation.

[February 2002]

### D.3.5.1 Use of Great Lakes Wave Runup Model

The runup analysis begins with the determination of significant wave conditions near the shore. The site must be categorized as one of three shore types typical of the Great Lakes: smooth vertical wall, rip-rap revetment having a single face slope, or sloping sand beach. For a revetment or beach, the characteristic slope, considered the grade of the slope from the mean

lake

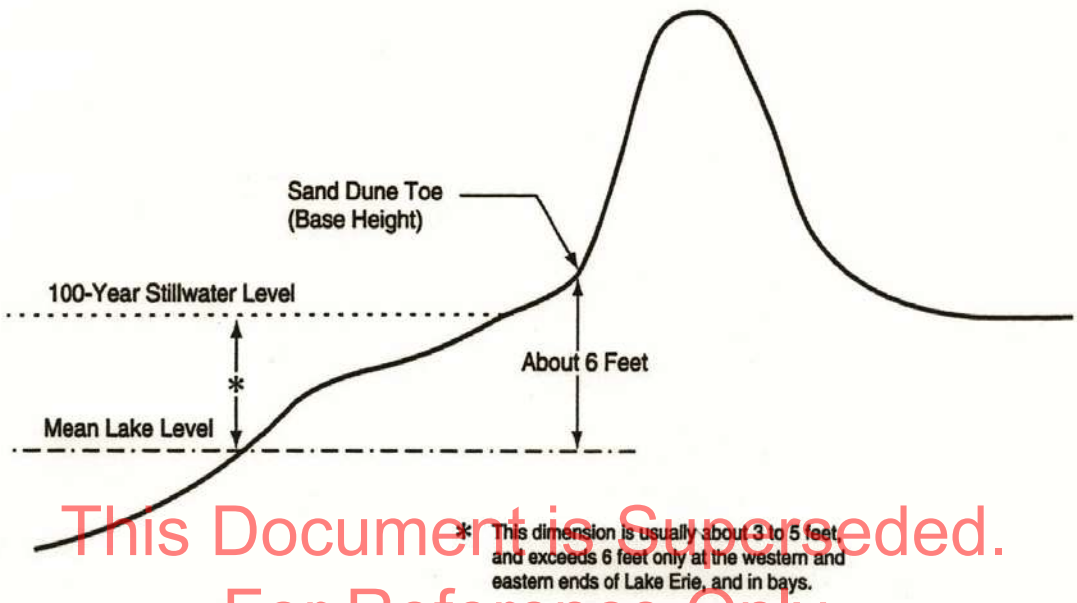


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**Figure D-40. Typical Great Lakes Coastal Geometry Prevents Wave Penetration Inland of Eroded Dune Site in Base Flood.**

level up to the 1-percent-annual-chance SWEL, must be determined. For a vertical structure or a sloping revetment, the wave conditions must be determined at the specified water depth of the structure toe and at a water depth of 26 feet for a sand beach. The depths to be used in analyzing wave conditions should be the depths of water below the local 1-percent-annual-chance flood level.

The wave runup elevation for the shore barrier can be estimated using the GLWRM, which is available from FEMA in digital format. The program executes step-by-step procedures for runup computation at Great Lakes sites, following the recommendations from the *Great Lakes Wave Runup Methodology Study* (USACE, June 1989). The interactive format occasionally prompts the user for input or review of hydraulic and topographic descriptions of a site, including the shore barrier specification, the 1-percent-annual-chance SWEL (see Subsection D.3.2.1), and offshore storm-wave characteristics (see Subsection D.3.2.6).

Tables D-15, D16, and D-17 present examples of computation input and output for the three distinct situations, namely, a vertical structure, a sloping revetment, and a sand beach.

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**Table D-15. Final GLWRM Results for Wave Runup on Vertical Structure. Diamonds Added to Identify Lines with Site Specific Specifications**

```
                 wave runup on ◆  vertical wall
      1% annual chance flood ◆ 582.6 feet
          water depth at toe ◆   5.5 feet
       3-year wave period  T ◆   9.1
                          T' :   2.6
                           L :  121.01
3-year deep water wave  H ◆  20.0 feet
                           K :   5.5
                       alpha :   0.0180
                         Hmo :   3.3
                       d bar :   0.0021
                     epsilon :   0.0068
                     Hs/Hmo ◆   0.907
            Hs at structure :   3.3
                        d/Lo :   0.0130
                     H/Ho' ◆   1.3500
                         Ho' :   2.4
                 Ho'/(gT**2) :   0.00090
                      ds/Ho' :   2.3
                   runup/Ho' :   2.58
        vertical wall runup :   6.2
            runup elevation : 588.8 feet
```

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**Table D-16. Final GLWRM Results for Wave Runup on Sloping Revetment. Diamonds Added to Identify Lines with Site Specific Specifications Input or Confirmed in Response to Interactive Screen Prompts.**

```
                wave runup on◆  revetment
   1% annual chance flood◆ 581.6 feet
       water depth at toe◆   4.5 feet
    3-year wave period  T◆   9.1
                       T' :   2.4
                        L: 109.45
3-year deep water wave  H◆  20.0 feet
                        K:   6.1
                    alpha:   0.0189
                      Hmo:   2.7
                    d bar:   0.0017
                  epsilon:   0.0062
                   Hs/Hmo◆   0.920
          H at structure:    2.7
              tan(theta)◆    0.22500
 revetment (Greek ltr) xi:   2.8
        revetment runup:     3.4
      runup elevation: 585.0 feet
```

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**Table D-17. Final GLWRM Results for Wave Runup onto Sand Beach. Diamonds Added to Identify Lines with Site Specific Specifications Input or Confirmed in Response to Interactive Screen Prompts**

```
                wave runup on◆  beach
   1% annual chance flood◆ 582.6 feet
       water depth at toe:  26.0 feet
    3-year wave period  T◆   9.1
                       T':   5.7
                        L: 263.09
3-year deep water wave  H◆  20.0 feet
                        K:   2.6
                    alpha:   0.0125
                      Hmo:   9.4
                    d bar:   0.0098
                  epsilon:   0.0089
                   Hs/Hmo◆   1.084
          Hs in deep water:  10.2
              beach slope◆   0.17300
beach (Greek ltr) xi:        1.115
              beach runup:   11.0
         runup elevation: 593.6 feet
```

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### D.3.5.2 Additional Considerations

As mentioned earlier in this Appendix, the GLWRM treats three shore configurations: smooth vertical wall, rip-rap revetment having a single face slope, or sloping sand beach. For some studies, the Mapping Partner may be required to evaluate other shore situations (e.g., grass or gravel shore slopes, mounds formed of other material or with a compound front slope). Although other methods and models for determining wave runup elevations could be used (see USACE, 1984 and 1992; Dewberry & Davis, 1991), the GLWRM runups can be adjusted to analyze these other shore situations. Using the GLWRM will provide consistency of results within a single study.

One parameter frequently used in NFIP coastal assessments is a roughness coefficient measuring barrier surface effects along the runup excursion (Dewberry & Davis, 1995; Stone & Webster, 1981). Table D-18 presents typical values of the roughness coefficient, usually designated as r, for common barrier materials. Wave runup elevation is assumed to vary directly with roughness coefficient, given no other difference in the geometrical configuration. Thus, GLWRM results for a sand beach (having a situation otherwise identical to that shown in Table D-13) may be multiplied by 0.90 to apply with grass, or by 0.70 to apply with gravel. For relatively steep slopes common to manmade shore structures, GLWRM results for a rip-rap revetment might be adjusted for application with other construction materials, using the appropriate ratio between roughness coefficients. Expressed formally, the runup on a rough surface is given as r times runup for a smooth surface, so that for rip-rap

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$$R_1 = r_1 R \tag{1}$$

and for some other rough barrier material

$$R_o = r_o R = r_o R_1/r_1 \tag{2}$$

where the value $R_1$ is obtained directly from the GLWRM.

Another simplification long employed in NFIP coastal assessments is the composite-slope method (Saville, 1958), where a hypothetical uniform slope is taken to represent the segmented barrier profile (Figure D-41). That equivalent slope customarily extends from the water depth with initial wave breaking to the limit of wave runup, or from a water depth equal to incident wave height when waves do not break (at a very steep shore). For a man-made structure, the GLWRM assumes a clearly identifiable toe or seaward limit to the wave barrier, so it is appropriate to start the equivalent uniform slope at that point. Because the landward limit assumed for the uniform slope is at the runup limit, some manual computation may be needed in iterative adjustment of the input slope to attain suitable consistency with calculated runup elevation.

**Table D-18. Appropriate Values for Roughness Coefficient in Wave Runup Calculations**

| ROUGHNESS COEFFICIENT | DESCRIPTION OF BARRIER SURFACE |
|---|---|
| 1.00 | Sand; smooth rock, concrete, asphalt, wood, fiberglass |
| 0.95 | Tightly set paving blocks with little relief |
| 0.90 | Turf, closely set stones, slabs, blocks |
| 0.85 | Paving blocks with sizable permeability or relief |
| 0.80 | Steps; one stone layer over impermeable base; stones set in cement |
| 0.70 | Coarse gravel; gabions filled with stone |
| 0.65 | Rounded stones, or stones over impermeable base |
| 0.60 | Randomly placed stones, two thick on permeable base |
| 0.50 | Cast-concrete armor units: cubes, dolos, quadripods, tetrapods, tribars, etc. |

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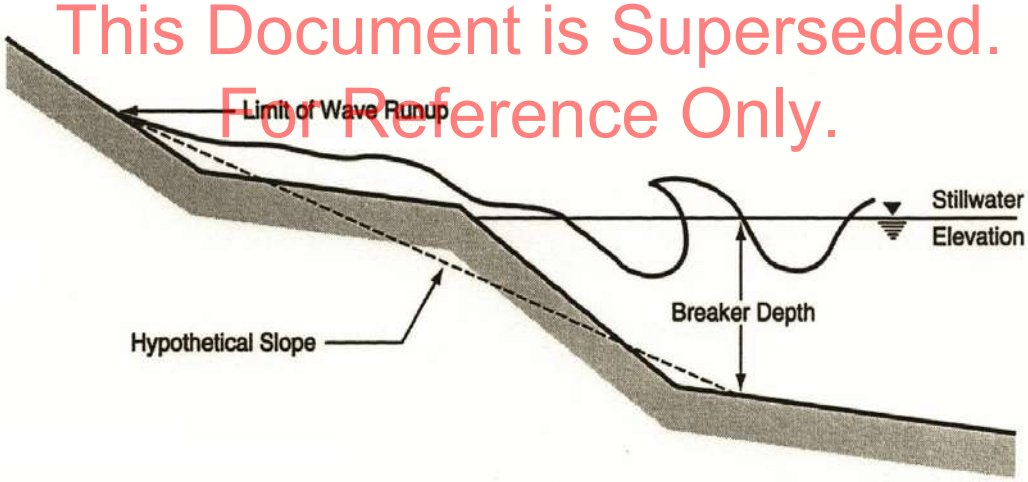


**Figure D-41. Hypothetical Slope for Determining Wave Runup on Composite Profiles.**

Once a definite runup elevation has been obtained for the shore situation, the Mapping Partner must compare it with barrier crest elevation to assess the possibility of wave overtopping. The examination takes into account that calculated runup elevation refers to common rather than extreme water excursions on the barrier, whereas all expected hazards of the 1-percent-annual-chance flood must be projected. If wave runup elevation reaches more than halfway from the stillwater level to the barrier crest, the Mapping Partner shall perform an overtopping assessment for flood hazards because likely wave runups occasionally will proceed over the shore barrier. Overtopping discharges in storm conditions may be estimated using empirical results in *Random Seas and Design of Maritime Structures* (Goda, 1985) for vertical walls, in "Design of Seawalls Allowing for Wave Overtopping" (Hydraulics Research Station, 1980) for sloping structures, and in "Wave Runup and Overtopping at Dunes during Extreme Storm Surge" (Delft Hydraulics Laboratory, 1983) for sand dunes with common erosion geometry. The Mapping Partner shall evaluate the effects of the discharge in terms of potential wave impacts, runoff depths, or ponding areas on ground landward of the shore barrier.

A distinct type of overflow situation can occur at low bluffs or banks backed by a nearly level plateau, where calculated wave runup may appreciably exceed the top elevation of the steep barrier. A memorandum entitled "Special Computation Procedure Developed for Wave Runup Analysis for Casco Bay, FIS - Maine, 9700-153" provides a simple procedure to determine realistic runup elevations for such situations, as illustrated in Figure D-42 (French, 1982). An extension to the bluff face slope permits computation of a hypothetical runup elevation for the barrier, with the imaginary portion given by the excess height $R' = (R\text{-}C)$ between calculated runup and the bluff crest. Using that height $R'$ and the plateau slope $m$, Figure D-43 defines the inland limit to wave runup, $X$, corresponding to runup above the bluff crest of ($mX$) or an adjusted runup elevation of $R_a = (C + mX)$. This procedure is based on a Manning's "n" value of 0.04 with some simplifications in the energy grade line and is meant for application only with positive slopes landward of the bluff crest. A different treatment of wave overflow onto a level plateau, for possible FIS usage, is provided in "Overland Bore Propagation Due to an Overtopping Wave" (Cox & Machemehl, 1986).

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A less common situation on the Great Lakes is that calculated wave runup exceeds a relatively high barrier crest backed by negative slopes. In such cases, a general rule limits the appropriate runup elevation to 3 feet above maximum ground elevation. Floodwaters overtopping the barrier percolate into the bed, or run along the back slope until encountering another flooding source or a ponding area. A runoff area is usually designated as Zone AO, with depth of flooding of 1, 2, or 3 feet; a ponding area may be designated as Zone AH, with a flood elevation. Standardized NFIP procedures have been developed for the treatment of sizable runoff and ponding, but are beyond the scope of this presentation; see *Guidelines and Specifications for Wave Elevation Determination and V Zone Mapping* (FEMA, 1995).

Aside from these considerations relating to the inland limit of flooding from wave runup and overtopping, the Mapping Partner must integrate the runup elevation at the shore barrier with calculated wave crest elevations near the shore.

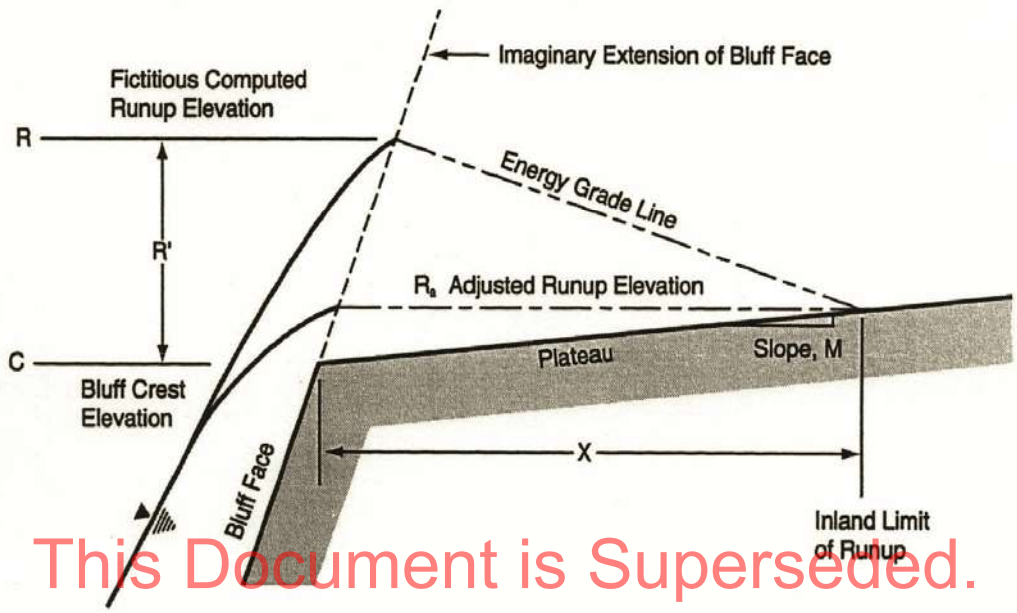


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**Figure D-42. Treatment of Wave Runup onto Plateau above Low Bluff.**

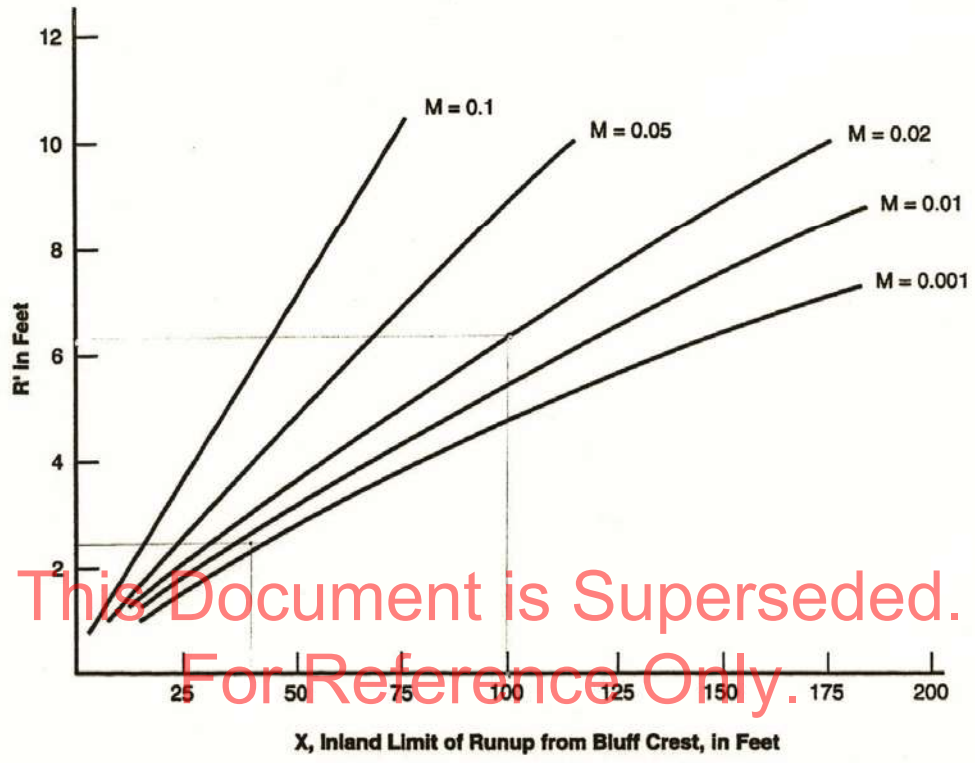


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**Figure D-43. Computation of Wave Runup for Low Bluffs.**

## D.3.6 Nearshore Wave Dimensions

As waves propagate near the shore and over a flooded area, they undergo transformations caused by local winds, interaction with the bottom, and physical features such as buildings, trees, or marsh grass. Figure D-44 illustrates the effects at a transect of obstructions on the wave crest elevations and the flood zone. For Great Lakes coasts, the effects must be calculated objectively along each transect, from the Low Water Datum to the flooding limit. Fundamental analysis of wave effects for an FIS is provided by the FEMA computer program Wave Height Analysis for Flood Insurance Studies (WHAFIS). The program calculates wave heights, wave crest elevations, flood hazard zone designations, and the location of zone boundaries along a transect. The current program version for the Great Lakes region, WHAFIS 3.0 GL, incorporates windspeeds appropriate to Great Lakes events (40 mph over fully exposed waters and 30 mph for inland waters or marsh).

Wave description for an FIS addresses the controlling wave height, equal to 1.6 times the significant wave height common as a basic wave description, with the dominant (or spectral peak) wave period. Significant wave height is the average height of the highest one-third of waves, and controlling wave height is slightly less than average height of the highest one percent of waves in storm conditions. The wave condition of interest is that expected to accompany the 1-percent-annual-chance flood.

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Within WHAFIS, a wave action conservation equation governs wave regeneration caused by wind and wave dissipation caused by marsh plants. This equation is supplemented by the conservation of waves equation, which expresses the spatial variation of the wave period at the peak of the wave spectrum. The wave energy (i.e., wave height) and wave period respond to changes in wind conditions, water depths, and obstructions as a wave propagates. These equations are solved as a function of distance along the transect. Technical details are fully documented in the WHAFIS program documentation (FEMA, September 1988).

The current NFIP treatment of wave dimensions has resulted from periodic upgrades of technical procedures, with the original basis being the NAS methodology documented in *Methodology for Calculating Wave Action Effects Associated with Storm Surges* (NAS, 1977). The NAS methodology, which was developed to be suitable for manual computations, accounts for varying fetch lengths, barriers to wave transmission, and the regeneration of waves over flooded land areas. Several aspects of usual Great Lakes situations suggest that simplified analysis, considering only water depth and thin vertical barriers, might give a useful outline of wave effects for some sites.

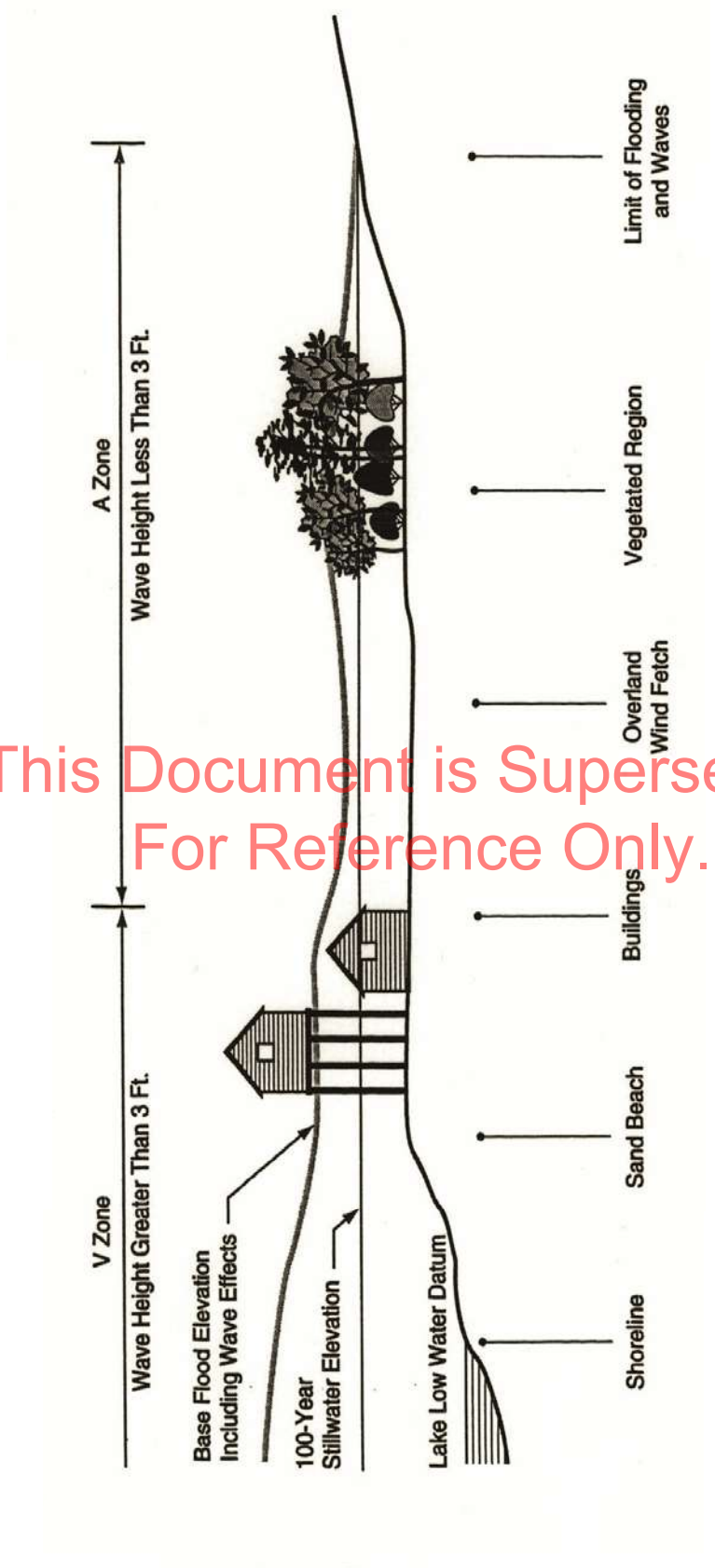


**Figure D-44. Schematic Wave Effects along a Coastal Transect.**

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### D.3.6.1 Simplified Wave Height Analysis

The potential usefulness of the simplified wave analysis method for treating 1-percent-annual-chance flood waves is suggested by certain aspects of the Great Lakes situation: the relatively low windspeeds, reducing the intensity of wave regeneration; the relatively simple eroded geometries, which are generally featureless lakeward of the ultimate flood barrier; the absence of barrier islands and back bays so that another flood source or elevation is seldom encountered; and the typical narrowness of the Coastal High Hazard Area. This method would not be appropriate where the transect includes coastal wetlands, other land cover providing appreciable flow resistance, or an extensive lowland area liable to flooding. Before any wave analysis, there must be confirmation that sizable waves likely propagate towards shore during the local 1-percent-annual-chance flood.

All elements of this treatment are extracted from the basic NAS methodology (Dawdy & Maloney, 980; FEMA, February 1981; NAS, 1977), with wave heights entirely regulated by local water depth. The estimated flood elevation (Z) is defined by wave action accompanying the flood, with the majority of the waveform in the crest above the 1-percent-annual-chance SWEL (S):

$$Z = S + 0.7\ H \tag{3}$$

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where H is the local controlling wave height. A bound to H is given by wave breaking in shallow water, with the upper limit

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$$H_* = 0.78\ d \tag{4}$$

where local water depth (d) equals (S-G), G being ground elevation. Combining these relations, local ground elevation constrains the flood elevation to an upper limit of

$$Z_* = S + 0.55\ d \tag{5}$$

Equation (4) implies that a minimum water depth of 3.85 feet is required for the 3-foot wave height characterizing a V Zone.

An obstruction on the transect may conveniently be treated as a thin barrier if flooding occurs to the same S on each side. Wave transmission is assumed to occur only if the barrier top elevation (C) is below S plus one-half the incident wave height ($H_i$). Transmitted wave height is

$$H_t = 0.5\ H_i + B \tag{6}$$

where B = ½[0.78 (S-C)] if the barrier is submerged, but B=[(S-C)] otherwise; the upper limit of $H_t = H_i$ occurs when $H_i$ is less than [0.78 (S-C)], requiring that $H_i$ is not depth-limited. Transmitted wave height beyond the barrier remains limited by ground elevation on the landward side of the barrier ($G_t$), through Equation (2), just as incident wave height is limited by

ground elevation on the lakeward side ($G_i$). With engineering judgment, wave obstructions other than walls might be represented by proper choices of $G_i$, C, and $G_t$ in this procedure.

Figure D-45 presents an idealized numerical example demonstrating estimated wave heights, flood elevations, and flood zones. Note that varying elevations of depth-limited wave crests mirror the ground slopes.

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### D.3.6.2 Use of WHAFIS 3.0 GL Model

Careful preparation and input of required site data are necessary in using WHAFIS. Like the other coastal treatments, the WHAFIS model considers the study area by representative transects. For WHAFIS, transects must be defined considering major topographic, vegetative, and cultural features. The transect, referenced to NGVD29, begins at the local elevation of Low Water Datum (Table D-13) and proceeds landward until either the ground elevation exceeds the SWEL or another flooding source is encountered.

Fundamental specifications for WHAFIS input include the 1-percent-annual-chance flood SWEL and a description of waves existing at the transect start. The wave description provides for an overwater fetch length, an initial significant wave height, or an initial period of dominant waves. In most Great Lakes applications, the wave period should be the input description, because that parameter is readily available from information about offshore waves (see Subsection D.3.2.6).

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The Mapping Partner shall locate transects on the work maps and plot the transect ground profile from the topographic data, adjusted for erosion. The Mapping Partner shall ensure that each transect has all the input data identified on the profile plot for ease of input coding. The Mapping Partner also shall identify the location, height, and width of elongated manmade structures and show them as part of the ground profile, after confirming the structure's stability under forces of the 1-percent-annual-chance flood (see Subsection D.3.3).

Buildings are specified on the transect as rows perpendicular to the transect. Because buildings are not always situated in perfect rows, the Mapping Partner shall exercise judgment to determine which buildings can be represented by a single row. The required input value for each row of buildings is the ratio of open space to total space. This is simply the sum of distances between buildings in a row, divided by the total length of that row.

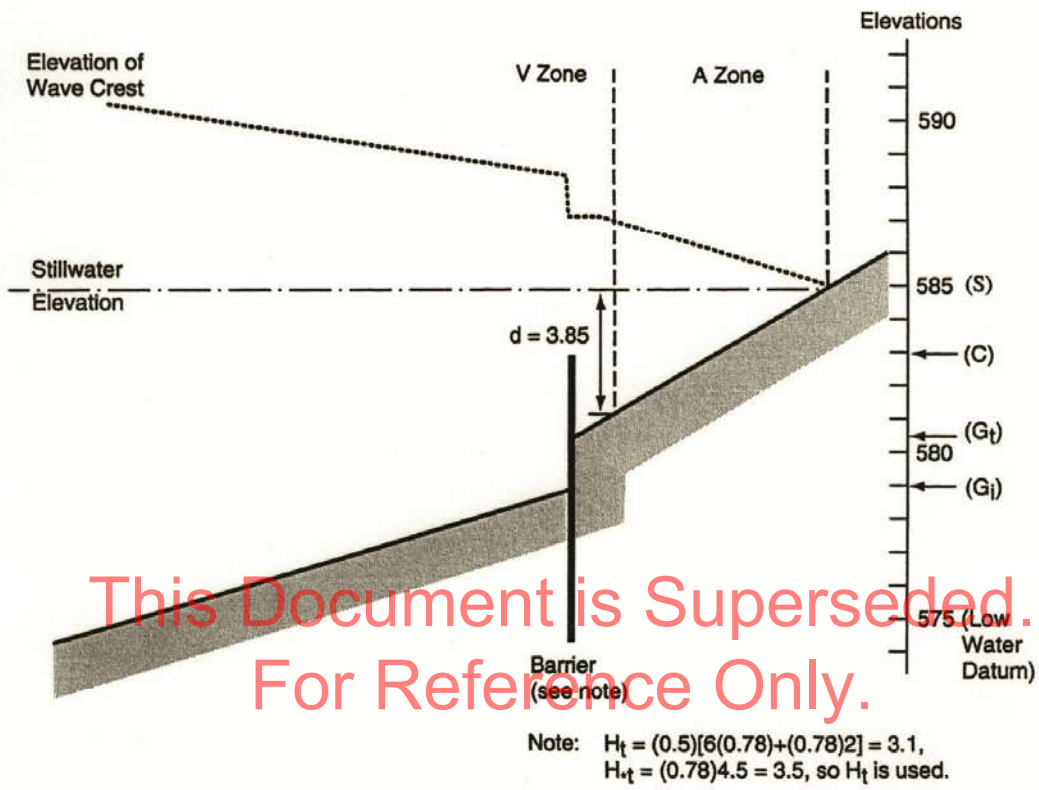


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**Figure D-45. Schematic Example of Simplified Wave Height Analysis Regulated by Local Water Depth, with All Indicated Quantities in Feet.**

The first row or two of buildings along the shoreline is not always to be considered as obstructions. During a 1-percent-annual-chance flood, it is sometimes appropriate to assume that if they are not elevated on pilings, these buildings will be destroyed before the peak of the flood occurs. If they are elevated, the waves should propagate under the structures with minimal reduction in height. The Mapping Partner shall contact local officials to obtain typical construction methods and the lowest elevations of structure.

The WHAFIS program has two routines for vegetation: one for rigid vegetation that can be represented by an equivalent "stand" of equally spaced circular cylinders (NAS, 1977) and one for marsh vegetation that is flexible and oscillates with wave action (FEMA, 1984). For either type, considerable care is required in selecting representative parameters and in ruling out that the vegetation will be intentionally removed or that effects during a storm would be markedly reduced through erosion, uprooting, or breakage.

For the areas of rigid vegetation located on the transect, the required input values are the drag coefficient, CD; mean wetted height, h; mean effective diameter, D; and mean horizontal spacing, b. The value of CD should vary between 0.35 and 1.0, with 1.0 being used in most cases of wide vegetated areas. When the vegetation is in a single stand, a value of 0.35 should be used. Representative values for h, D, and b can be obtained from stereoscopic aerial photographs or by field surveys. Various guides for terrain analysis can provide procedures for estimating these values from aerial photographs. Table D-19 provide a useful procedure developed from Terrain Analysis Procedural Guide for Vegetation (Messmore, Vogel, & Pearson, 1979).

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For marsh vegetation, a more complicated specification is required for completeness, and the eight parameters used to describe the attenuation properties of a specific vegetation type are explained in Table D-20.

WHAFIS includes considerable basic information on eight common types of seacoast marsh plants listed in Table D-21 (FEMA, 1984; FEMA, 1989), but among these, apparently only the *Juncus* species are likely to occur in the freshwater marshes on the Great Lakes. For vegetation not listed in Table D-21, the Mapping Partner shall input the geometrical parameters to WHAFIS.

At lakeshore elevations that are seldom flooded and thus are important for the 1-percent-annual-chance flood, a great diversity of wetland vegetation can occur along with upland vegetation species. Prevalent marsh plants at relatively high elevations (Levels Reference Study Board) may include combinations of grasses (*Phalaris arundinacea*, *Calamagrostis canadensis*), sedges (*Carex lacustris*, *C. rostrata*, *C. stricta*, *C. lasiocarpa*), rushes (*Juncus canadensis*, *J. effusus*), or cattails (*Typha* varieties). The Mapping Partner shall specify each existing type of vegetation s, along with its fractional coverage in any sizable patch; a patch of at least 10,000 square feet (0.09 hectare) can affect wave heights appreciably.

**Table D-19. Procedure for Vegetation Analysis Using Stereoscopic Aerial Photographs.**

1. Using the parallax bar or wedge, determine the height of three representative trees and compute the average height, h.

2. Locate three representative tree crowns, measure the diameters, and compute the average crown diameter, CD.

3. Determine the type of vegetation and calculate the stem diameter, D, using the following formulae:

   Southern Pines — D (inches) = 5 + 0.5 CD (feet)

   Eastern Hardwoods,
   Northern Pines and Others — D (inches) = 0.75 CD (feet)

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4. Based on the scale of the aerial photographs, determine the diameter of a circle containing 0.08 hectares using Table 4. Place the circle on the photograph, over a representative area of trees, and count the number of trees, n, in the circle. A magnifier may be needed. More than one area can be counted and an average used for n. Calculate the number of trees per hectare, N, using the following formula:

$$N = \frac{n}{0.08}$$

5. Determine the horizontal spacing between trees using the following formula:

$$b \text{ (feet)} = 3.28 \left( \frac{12732}{N} \right) - \frac{D \text{ (inches)}}{12}$$

**Table D-19. Procedure for Vegetation Analysis Using Stereoscopic Aerial Photographs (Cont.)**

CIRCLE DIAMETERS
.08 HECTARE AREA, (1/5 ACRE)
(800 Square Meters, 8712 Square Feet)

| PHOTO SCALE | .08 HECTARE CIRCLE | CIRCLE DIAMETER INCHES | CIRCLE DIAMETER MILLIMETERS |
|---|---|---|---|
| 1:5,000 | | .253 | 6.38 |
| 1:6,000 | | .211 | 5.32 |
| 1:7,000 | | .1805 | 4.56 |
| 1:8,000 | | .158 | 3.99 |
| 1:9,000 | | .140 | 3.55 |
| 1:10,000 | | .126 | 3.192 |
| 1:11,000 | | .115 | 2.90 |
| 1:12,000 | | .105 | 2.66 |
| 1:13,000 | | .092 | 2.46 |
| 1:14,000 | | .090 | 2.28 |
| 1:15,000 | | .084 | 2.13 |
| 1:16,000 | | .079 | 1.99 |
| 1:17,000 | | .074 | 1.88 |
| 1:18,000 | | .070 | 1.77 |
| 1:19,000 | | .067 | 1.68 |
| 1:20,000 | | .063 | 1.60 |
| 1:21,000 | | .060 | 1.52 |
| 1:22,000 | | .057 | 1.45 |
| 1:23,000 | | .055 | 1.39 |
| 1:24,000 | | .053 | 1.33 |
| 1:25,000 | | .051 | 1.28 |

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**Table D-20. Marsh Plant Parameters**

| PARAMETER | EXPLANATION |
|---|---|
| $C_D$ | Effective drag coefficient. Includes effects of plant flexure and modification of the flow velocity distribution. Default value is 0.1, usually appropriate for marsh plants without strong evidence to the contrary. |
| $F_{cov}$ | Fraction of coverage. A default value is calculated by the program so that each plant type in the transect is represented equally, and the sum of the coverage for the plant types is equal to 1.0. |
| h | Unflexed stem height (feet). The stem height does not include the flowering head of the plant, the inflorescence. |
| N | Number density. Expressed as plants per square foot. The relationship to the average spacing between plants, b, can be expressed as $N = 1/b^2$. |
| $D_1$ | Base stem diameter (inches). Default value may be determined from stem height and regression equations built into the program. |
| $D_2$ | Mid stem diameter (inches). Default value may be determined from plant type and base stem diameter. |
| $D_3$ | Top stem diameter (inches), at the base of the inflorescence. Default value may be determined from plant type and base stem diameter. |
| $CA_b$ | Ratio of the total frontal area of the cylindrical portion of the leaves to the frontal area of the stem below the inflorescence. Default value may be determined from the plant type. |

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**Table D-21. Abbreviations of Marsh Plant Types Used in WHAFIS**

| SPECIES OR SUBSPECIES | ABBREVIATION |
|---|---|
| *Cladium jamaicense* (saw grass) | CLAD |
| *Distichlis spicata* (salt grass) | DIST |
| *Juncus gerardi* (black grass) | JUNM |
| *Juncus roemerianus* (black needlerush) | JUNR |
| *Spartina alterniflora* (medium saltmeadow cordgrass) | SALM |
| *Spartina alterniflora* (tall saltmeadow cordgrass) | SALT |
| *Spartina cynosuroides* (big cordgrass) | SCYN |
| *Spartina patens* (saltmeadow grass) | SPAT |

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### D.3.6.3 Input Coding

After all the necessary input data have been identified on the transect, the Mapping Partner shall divide the transect into continuous segments, each representing a single open fetch or obstruction. Fetches are flooded areas with no obstructions, such as dunes, manmade barriers, buildings, and vegetation. The Mapping Partner shall subdivide fetches at points where the ground elevation abruptly changes and in the transition area of changing SWELs. The Mapping

Partner shall subdivide obstructions at the transect's seaward edge to more accurately model the wave dissipation. Rigid vegetation is to have two to three seaward segments extending 10 to 50 feet, and the first two or three rows of buildings are to have a segment for each row. Marsh vegetation will be subdivided by the WHAFIS model, and thus segmented input is not necessary.

The Mapping Partner shall enter the necessary data using 11 line types, including the Title line. The ten remaining lines each describe a certain type of fetch or obstruction, listed as follows:

- The IE (Initial Elevation) line describes the initial overwater fetch and the initial SWELs.
- The IF (Inland Fetch) and OF (Overwater Fetch) lines define the endpoint stationing and elevation of inland and overwater fetches, respectively.
- Obstructions are categorized either as buildings (BU line), rigid vegetation (VE line), marsh vegetation (VH and MG lines), dunes and other natural or manmade elongated barriers (DU line), or areas where the ground elevation is greater than the 1-percent-annual-chance SWEL (AS line).
- The ET (End of Transect) line enters no data but indicates the end of the input data.

Each line has an alphanumeric field describing the type of input for that line, followed by ten numeric fields describing the parameters.

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To ensure proper modeling, the Mapping Partner shall enter all segments of each transect either as fetches or obstructions, with one input line required for each fetch or obstruction segment. The first two columns of each line identify the type of fetch or obstruction. The remaining 78 columns consist of one field of six columns followed by nine fields of eight columns. The Mapping Partner shall right-justify the numbers in any data field only if no decimal point is used. Decimal points are permitted but not required. The end point of one fetch or obstruction is the beginning of the next. The first two numeric fields of each line are used to read in the stationing (measured in feet from the beginning of transect) and elevation (in feet) of the end point. The last two fields used on each line are for entering new SWELs. An interpolation is performed within a transect segment starting at the closest station with an input SWEL. This interpolation uses the new SWEL input at the end point of the segment and the SWEL input at a previous segment. If these fields are blank or zero, the SWELs remain unchanged.

The input data requirements are summarized below for each line type. The Title line must be the first line, followed by the IE line, followed by any combination of the various fetch and obstruction lines. The ET line must be the last card entered for the transect. A blank line must follow to signify the end of the run. If multiple transects are being run, the Title line for the next transect will follow the blank line. All units are in feet unless otherwise specified.

<u>TITLE Line (Title)</u>

This line is required and must be the first input line.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | Blank |
| 1-10 | 3-80 | Title information centered about column 40 |

IE Line (Initial Elevations)

This line is required and must be the second input line. This line is used to begin a transect at the shoreline and compute the wave height arising through the overwater fetch.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | IE |
| 1 | 3-8 | Stationing of end point of initial overwater fetch in feet (zero at beginning of transect) |
| 2 | 9-16 | Ground elevation at end point in feet (usually Low Water Datum at beginning of transect) |
| 3 | 17-24 | Overwater fetch length (miles), if wave condition is to be calculated. Values of 24 miles or greater yield identical results. |
| 4 | 25-32 | 10-percent-annual-chance SWEL in feet |
| 5 | 33-40 | 1-percent-annual-chance SWEL in feet |
| 6 | 41-48 | Initial wave height; a blank or zero causes a default to a calculated wave height |
| 7 | 49-56 | Initial wave period (seconds); a blank or zero causes a default to a calculated wave period. The period is usually the most convenient wave specification for Great Lakes cases. |
| 8-10 | 57-80 | Not used |

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AS Line (Above Surge)

This line is used to identify the end point of an area with ground elevation greater than the 1-percent-annual-chance SWEL (such as a high dune or land mass). It is used when the ground surface temporarily rises above the 1-percent-annual-chance SWEL. The line immediately preceding the AS line must enter the stationing and elevation of the point at which the ground elevation first equals the 1-percent-annual-chance SWEL. The SWEL on the leeward side may be different from the SWEL on the windward side. The ground elevation entered on the AS line must equal the SWEL that applies to the leeward side of the land mass. The computer calculations will be terminated if a ground elevation greater than the 1-percent-annual-chance SWEL is encountered.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | AS |
| 1 | 3-8 | Stationing at end point in feet of area above 1-percent-annual-chance SWEL |
| 2 | 9-16 | Ground elevation in feet at end point |
| 3 | 17-24 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to the 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

BU Line (Buildings)

This line enters information needed to compute wave dissipation at each group of buildings.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | BU |
| 1 | 3-8 | Stationing of end point in feet of group of buildings |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | Ratio of open space between buildings to total transverse width of developed area |
| 4 | 25-32 | Number of rows of buildings |
| 5 | 33-40 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 6 | 41-48 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 7-10 | 49-80 | Not used |

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DU Line (Dune)

This line enters information necessary to compute wave dissipation at substantial sand dunes and other natural or manmade elongated barriers (e.g., levees, seawalls).

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | DU |
| 1 | 3-8 | Stationing at top of dune or barrier in feet |
| 2 | 9-16 | Elevation at top of dune or barrier in feet |
| 3 | 17-24 | A blank or zero indicates a dune or other natural barrier; any other number indicates a seawall or other manmade barrier |
| 4 | 25-32 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 5 | 33-40 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; |

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| | | otherwise new 1-percent-annual-chance SWEL |
| 6-10 | 41-80 | Not used |

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## IF Line (Inland Fetch)

This line enters the parameters necessary to compute wave regeneration through inland fetches and over shallow inland waterbodies. The IF regeneration is computed using overland wind speed of 30 mph for Great Lakes floods.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | IF |
| 1 | 3-8 | Stationing at end point of fetch in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

## OF Line (Overwater Fetch)

This line enters the parameters necessary to compute wave regeneration over large bodies of water (i.e., large lakes, bays) using overwater wind speed of 40 mph for Great Lakes floods. If an inland waterbody is sheltered and has a depth of ten feet or less, the IF line calling for overland wind speeds should be used.

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| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | OF |
| 1 | 3-8 | Stationing at end point of fetch in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 4 | 25-32 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 5-10 | 33-80 | Not used |

## VE Line (Vegetation)

This line enters parameters necessary to compute wave dissipation due to rigid vegetation stands.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | VE |
| 1 | 3-8 | Stationing at end point of vegetation in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | Mean effective diameter of equivalent circular cylinder in feet |
| 4 | 25-32 | Average actual height of vegetation in feet |
| 5 | 33-40 | Average horizontal spacing between plants in feet |
| 6 | 41-48 | Drag coefficient; a blank or zero causes a default to 1.0 |
| 7 | 49-56 | A blank or zero indicates no change to 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 8 | 57-64 | A blank or zero indicates no change to 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 9-10 | 65-80 | Not used |

## VH Line (Vegetation Header for Marsh Grass)

Marsh grass is often part of a plant community that may consist of several plant types. The VH line is used to enter data that apply to all plant types modeled in the transect segment. To enter data for each plant type, MG lines for each plant type must follow the VH line.

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| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | VH |
| 1 | 3-8 | Stationing at end point of marsh vegetation segment in feet |
| 2 | 9-16 | Ground elevation at end point in feet |
| 3 | 17-24 | $Reg_p$, number of the primary seacoast region for default plant parameters. Leave blank for Great Lakes computations. |
| 4 | 25-32 | $Wt_p$, weighting factor for the primary seacoast region. Not applicable for Great Lakes analyses. |
| 5 | 33-40 | $Reg_s$, number of secondary seacoast region. Not applicable for Great Lakes analyses. |
| 6 | 41-48 | $N_{p1}$, number of plant types; range is 1 to 10, inclusive. One MG line is required for each plant type. |
| 7 | 49-56 | A blank or zero indicates no change to the 10-percent-annual-chance SWEL; otherwise new 10-percent-annual-chance SWEL |
| 8 | 57-64 | A blank or zero indicates no change to the 1-percent-annual-chance SWEL; otherwise new 1-percent-annual-chance SWEL |
| 9 | 65-72 | Not used |
| 10 | 73-80 | This field is for overriding the default method of averaging flood hazard factors in A Zones; if 1 in column 80, averaging process begins or ends at end of vegetation segment; otherwise, default averaging method is used |

MG Line (Marsh Grass)

This line is used to enter data for a particular plant type. The first MG line must be preceded by a VH line. For the common seacoast marsh grasses listed in Table D-21, potentially useful default values are supplied in Table D-22. If a plant type not listed in the table is used, then appropriate data must be developed for Fields 2-9.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | MG |
| 1 | 5-8 | Marsh plant type abbreviation (see Table 10) |
| 2 | 9-16 | $C_D$, effective drag Coefficient; default value is 0.1 |
| 3 | 17-24 | $F_{cov}$, decimal fraction of vegetated area to be covered by this plant type; a blank or zero causes a default to be calculated so that each plant type is represented equally |
| 4 | 25-32 | h, mean unflexed height of stem (feet); for marsh plants, the inflorescence is not included |
| 5 | 33-40 | N, number of plants per square foot |
| 6 | 41-48 | $D_1$, base stem diameter (inches) |
| 7 | 49-56 | $D_2$, mid stem diameter (inches) |
| 8 | 57-64 | $D_3$, top stem diameter (inches) |
| 9 | 65-72 | $CA_b$, ratio of the total frontal area of cylindrical part of leaves to frontal area of main stem |
| 10 | 73-80 | Not used |

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ET Line (End of Transect)

This line is required and must be the last input card because it identifies the end of input for the transect.

| DATA FIELD | COLUMNS | CONTENTS OF DATA FIELDS |
|---|---|---|
| 0 | 1-2 | ET |
| 3-10 | 3-80 | Not used |

**Table D-12. Significant Marsh Plant Types in Each Seacoast Region and WHAFIS Default Regional Plant Parameter Data**

| REGION NO. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| REGION NAME: | NORTH ATLANTIC | MID-ATLANTIC | SOUTH ATLANTIC | SOUTH FLORIDA | NORTHEASTERN GULF | DELTA PLAIN | CHENIER PLAIN | SOUTH TEXAS |
| CLAD | --- | --- | --- | 7.50(+)<br>0.0656<br>6 | 6.00(2)<br>0.0260<br>6 | --- | --- | --- |
| DIST | --- | 0.78(1)<br>0.0039<br>211 | 1.00(1)<br>0.038<br>243 | 1.00(+)<br>0.0038<br>248 | ---<br>--- | 1.08(4)<br>0.0035<br>102 | 1.08(+)<br>0.0035<br>102 | --- |
| JUNM | 1.23(1)<br>0.0042<br>300 | 1.23(+)<br>0.0042<br>300 | --- | --- | --- | --- | --- | --- |
| JUNR | --- | 2.95(+)<br>0.0095<br>147 | 2.95(+)<br>0.0095<br>147 | --- | 2.95(3)<br>0.0095<br>147 | 3.00(4)<br>0.0106<br>83 | 2.95(+)<br>0.0095<br>147 | --- |
| SALM | 1.39(1)<br>0.0184<br>45 | 1.06(1)<br>0.0103<br>36 | 1.63(1)<br>0.0141<br>12 | 1.63(+)<br>0.0141<br>12 | --- | 1.67(4)<br>0.0141<br>21 | 2.62(5)<br>0.0211<br>16 | --- |
| SALT | 1.86(1)<br>0.0175<br>37 | 2.21(1)<br>0.0169<br>18 | 3.20(1)<br>0.0183<br>10 | 3.20(+)<br>0.0183<br>10 | --- | 3.20(4)<br>0.0183<br>10 | 3.20(+)<br>0.0183<br>10 | --- |
| SCYN | --- | --- | 8.29(+)<br>0.0492<br>6 | --- | --- | 4.00(4)<br>0.0267<br>7 | --- | --- |
| SPAT | 1.03(1)<br>0.0025<br>409 | 0.85(1)<br>0.0019<br>327 | 1.65(1)<br>0.0019<br>236 | --- | 2.58(2)<br>0.0026<br>236 | 1.88(4)<br>0.0016<br>333 | 1.88(+)<br>0.0019<br>333 | --- |

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Data arranged in vertical triplets:

h, stem height below inflorescence, in feet
D, base diameter, in feet
N, number density, in inverse square feet

Parenthetical references indicate data source:

1 = Hardisky and Reimold, 1977
2 = Monte, August 1983
3 = Kruczynski, Subrahmanyam, Drake, 1978
4 = Hopkinson, Gosselink, Parrondo, 1980, Diameters extrapolated
5 = Turner and Gosselink, 1975, Diameters extrapolated
+ = Extrapolated Data
--- = Insignificant amounts of this plant type in the region

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### D.3.6.4 Error Messages

While using the WHAFIS program, the Mapping Partner may encounter the error messages listed below.

- "AS card ground elevation less than SWEL, should use other type card, job dumped."

  Only use AS (above surge) line when the ground elevation is above the SWEL. Can otherwise use IF, OF, BU, DU, VE, or VH.

- "Ground elevation greater than surge elevation encountered, job dumped."

  If ground elevation is above surge elevation, AS card should be used.

- "Average depth less than or equal to zero, job dumped."

  The water depth must be greater than zero or a wave height cannot be computed. Check the SWEL and the ground elevation if point of job dump is not the last point along the transect profile.

- "The above card contains illegal data in the first 2 columns."

  Check input data for incorrect values or input within wrong columns. Aside from the title line, the first two columns in each line should contain the card identifiers.

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- "Transmitted wave height at last fetch or obstruction = _____ which exceeds 0.5."

  Code the transect profile up to the inland limit where ground elevation intersects the SWEL so that wave height should decrease to zero. If the scope of work ends at the corporate limits before the ground elevation meets the SWEL, this message can be ignored.

- "Array dimensions exceeded. Job dumped."

  Size of the array is limited and the number of input parameters has exceeded the array. Check the number of input parameters at the location where the job dumped.

- "Invalid data in field 1 of IF card," etc.

  Check input data to make sure that data are in correct columns.

- "Wave period less than or equal to zero in subroutine fetch. Abort run."

  Either a fetch length or a wave period must be input for the program to run properly. Check input data.

- "Invalid data in field 3 or field 5 of VH card."
  Check input data.
- "Invalid data in field 4 of VH card."

  Check input data.

- "Invalid data in field 3 of MG card."

Check input data. The fraction of vegetated area covered by the stated plant type should be a decimal number between 0.0 and 1.0.

- "Missing MG card or incorrect data in field 6 of VH card."

  A MG card must always follow the VH card. Field 6 of the VH card pertains to the number of plant types, and one MG card is required for each plant type.

- "Invalid input data."

  Check input data for invalid characters, such as an O instead of a zero. Check to be sure that all data are in their correct columns.

- "Fcov was found to be negative for plant type = _____."

  Check input data to be sure that the decimal fraction of the vegetated area covered by the plant type is not negative.

- "Ncov is .LE. zero in Sub.Lookup when it should be .GT. zero. Abort run."

  Check input for number of plants covering the area.

- "The first card is not an IE card, this transect is aborted. Continued to next transect."

  The first card after the title line must always be an IE card. Check input data.

- "**** The surge elevation at this station (stationing ____), which is ____ card, is less than the ground elevation. The interpolation process is continued. *** Please double check the surge and ground elevations in the vicinity of this station!!!!!!"

  The surge elevation should not be below the ground elevation. If the interpolated surge elevation is interpolated below the ground elevation, insert additional cards to specify surge and ground elevations and use an AS card if necessary.

- "Interpolation line cuts off more than two portions of high ground ridge. This transect is aborted, re-assign 1-percent-annual-chance elevations at high ground stations."

  When the interpolated value falls below the ground elevation, insert additional cards to better model the area and set the SWEL equal to the ground elevation where appropriate. Insert AS cards as necessary.

- "**** Unreasonable high ground elevation at station ____ which is ____ card. This transect is aborted, continued to next transect. **** Double check the surge and ground elevations in the vicinity of this station. If the ground elevations are correct, either assign a higher surge elevation or use AS cards."

  Add additional input data as necessary to better define the ground elevation and surge elevation in this area.

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### D.3.6.5 Output Description

The output of the program provides all the data necessary for plotting the BFEs and flood insurance risk zones along the transect. The output is in six parts:

**Part 1 - Input**

This is a printout showing all input data lines and the parameters assigned to each line, both manually and by default. This is followed by a more detailed printout with column headings for each input data line. When VH and MG Lines are used, a separate insert will be printed directly beneath the MG Line showing any default values supplied by the computer.

**Part 2 - Controlling Wave Heights, Spectral Peak Wave Period, and Wave Crest Elevations**

This is a list of the calculated controlling wave heights, spectral wave peak periods, and wave crest elevations at the end point of each fetch and obstruction of the input, and at calculation points generated between the input stations.

**Part 3 - Location of Areas Above 1-Percent-Annual-Chance Surge**

This is a list of the locations of areas where the ground elevation is greater than the 1-percent-annual-chance stillwater (surge) elevation. Only areas identified by AS lines are listed.

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**Part 4 - Location of Surge Elevations**

This is a list of the 10- and 1-percent-annual-chance stillwater (surge) elevations and the stationing of the points where each set of SWELs first becomes fully effective.

**Part 5 - Location of V Zones**

This is a list of the locations of the V/A Zone boundary and locations of the V Zone areas relative to these boundaries. The stationing is given for each V/A Zone boundary. The locations of the V Zone areas in relation to these boundaries are given as windward or leeward of the boundary.

**Part 6 - Numbered A Zones and V Zones**

This is a list of the zone data needed to delineate the flood hazard boundaries on the FIRM. The location of a flood zone boundary and the wave crest elevation at that boundary are given on the left. Between the boundary listings are the zone designations and FHFs. Under FEMA's Map Initiatives Procedure guidelines, all numbered V and A Zones should be changed to VE and AE Zones, respectively (elevations will not change), and the FHFs can be ignored (FEMA, 1991). When the same zone and elevation are repeated in the list, they should be treated as a single zone.

[February 2002]

## D.3.7 Mapping of Flood Elevations and Zones

This subsection discusses procedures for reviewing the initial model results and identifying flood insurance risk zones, and provides guidance for depicting the analysis on the FIRM.

[February 2002]

### D.3.7.1 Review and Evaluation of Basic Results

The results of the technical analyses performed for the FIS or map revision determine the special flood hazards shown on the FIRM. The coastal hazards mapped on the FIRM depict the effects of erosion on overland wave propagation, the impact of steep beach slopes and bluffs on wave runup elevation, and the areas subject to high velocity wave hazards (V Zones). Because the FIRM is used for floodplain management and flood insurance determination, the Mapping Partner shall ensure the SFHAs are mapped with as much accuracy as possible.

With the results of the various analyses at hand, the Mapping Partner shall place flood elevations and zones on the work map or up-to-date topographic survey map, after first reviewed them for their consistency with the terrain and conditions they represent and with historical data. In using the models, it is possible to forget that the transects represent real shorelines of sandy beaches, rocky or cohesive bluffs, wetlands, etc., being subjected to extremely high water, waves, and winds. The Mapping Partner shall review the results of the analyses to determine if they are a reasonable representation of the coastal areas being modeled.

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Although historical data from a storm closely approximating the base (1-percent-annual-chance) flood are seldom available, flood data for less intense storms will still indicate, at a minimum, what areas should be in flood zones. For instance, if a storm produced an extreme flood that caused structural damage to houses 100 feet from the shoreline, yet the flood was below the 1-percent-annual-chance flood SWEL, a reasonable Zone VE width would be at least 100 feet. Similarly, houses more than 100 feet from the shoreline that are flooded but not structurally damaged by the same storm must be at least in a Zone AE, AH, or AO. If the analyses of the 1-percent-annual-chance flood produce flood zones and elevations indicating lesser hazards than those recorded for a more common storm, the Mapping Partner shall reevaluate the analyses. There may be an explanation for the inconsistency (other than an error in the input data); for instance, a new coastal structure may act to reduce flood hazards locally or a big storm may have significantly altered the terrain. A field check should be undertaken to determine whether such an explanation exists.

If no explanation for the inconsistency is apparent, the Mapping Partner shall examine the data input to the models including checking that the SWELs, wave heights, wave periods, and fetch lengths were input correctly and are consistent with the historical data. A further field check could examine whether buildings or structures modeled would be destroyed by the storm or whether the buildings are on pilings above the flooding.

The Mapping Partner also shall evaluate the results of the erosion assessment by comparing the eroded profile to past effects, whether in the form of profiles, photographs, or simply

descriptions. A general idea of what happened previously can be sufficient. Judgment and experience must be used to project previous storm effects to the 1-percent-annual-chance flood conditions and to ensure that the eroded profile is consistent with previous events.

The main point emphasized here is that the results are not to be blindly accepted. Many uncertainties and variables in coastal processes may occur during an extreme flood, and many possible adjustments to methodologies for treating such an event may be appropriate. The validity of any model is demonstrated by its success in reproducing recorded events. Therefore, the model results must be in basic agreement with past flooding patterns and results, and historical data must be used to evaluate these results.

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### D.3.7.2 Identification of Flood Insurance Risk Zones

Interpretation and accurate delineations of the hazards on the maps are the final critical elements in a coastal flood hazard study. The transect used in the wave elevation determination and the resulting wave analyses, whether for wave height or wave runup, is the tool by which the results can be mapped. Mapping Partner shall identify the flood zones and BFEs should be identified on each of the transect plots before transferring the information and delineating the hazard zones and BFEs on the work maps. It should be noted that because of changes in the NFIP in 1988 that redefined the Coastal High Hazard Area and incorporated wave runup hazards, Part 6 of the WHAFIS output, discussed in Section D.3.6, is no longer used to plot zones on the work maps.

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It is important to understand the interrelationship of the three key elements in determining the flood hazard zone and BFE. These elements are the existing transect ground profile, the eroded transect ground profile, and the wave envelope. The existing transect ground profile may be modified by the presence of erosion forces along the shoreline, if appropriate, in which case the flood hazard zone depicted by the transect and wave analyses results may not appear to reflect the topography shown for existing conditions with ground elevations higher than the BFE. The eroded transect ground profile, developed using treatment described in Subsection D.3.4, must be used in the wave analyses described in Subsections D.3.5 and D.3.6. The BFEs and the topography shown on the work maps may differ from those produced by the erosion treatments for a shoreline reach and the wave analyses. This is because the topography of the work maps does not reflect the erosion of the shoreline determined as part of the coastal FIS or map revision request. To clarify areas where these discrepancies exist, the Mapping Partner shall provide a description of the areas subject to erosion treatments either in the coastal FIS Report or in the supporting engineering report for a map revision request.

The wave envelope is the most important of the three elements for identifying the flood hazard zone. The wave envelope is a combination of representative wave runup elevation and the wave crest profile determined by the wave results computed using the WHAFIS program. The wave crest profile is plotted on the final transect ground profile (with or without the effects of erosion) based on the results computed and shown in Part 2 of the WHAFIS output. For wave runup elevation results, a horizontal line is extended seaward from the computed runup elevation to its intersection with the wave crest profile. This determines the wave envelope profile for the

results combined from the WHAFIS wave height analysis and the RUNUP 2.0 wave runup analysis, as shown in Figure D-46. If the runup elevation is greater than the maximum wave crest elevation, the wave envelope will be a horizontal line at the runup elevation. Conversely, if the wave runup is negligible or was not modeled because of coastal processes and shoreline conditions that prevent significant runup from occurring, the wave crest profile alone will become the wave envelope.

Before transferring the established wave envelope information from each transect onto the work maps, it is important to understand the NFIP coastal flood zones and how to determine their location along the transect plot. The descriptions are as follows:

Zone VE - Coastal High Hazard Areas where wave action and/or high velocity water can cause structural damage in the base (1-percent-annual-chance) flood. The three criteria for determining a Zone VE area are: (1) the area where 3 foot or greater wave height could occur (this is the area where the WHAFIS wave crest profile is 2.1 feet or more above the SWEL), (2) the area where the eroded ground profile is 3 feet or more below the representative runup elevation, and (3) the primary frontal dune, by definition. Subdivided into elevation zones with BFEs assigned.

Zone AE - Areas of inundation by the base (1-percent-annual-chance) flood, including wave heights less than 3 feet and runup elevations less than 3 feet above the ground. Also subdivided into elevation zones with BFEs assigned.

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Zone AH - Areas of shallow flooding or ponding, with water depth equal to 3 feet or less. Usually not subdivided, but a BFE is assigned.

Zone AO - Areas of "sheet-flow" shallow flooding where overtopping water flows into another flooding source. Assigned with 1-, 2-, or 3-foot depth of flooding.

Zone X - Areas above base (1-percent-annual-chance) flood inundation. On the FIRM, shaded Zone X is inundated by the 0.2-percent annual chance flood, unshaded Zone X is above 0.2-percent annual chance flood.

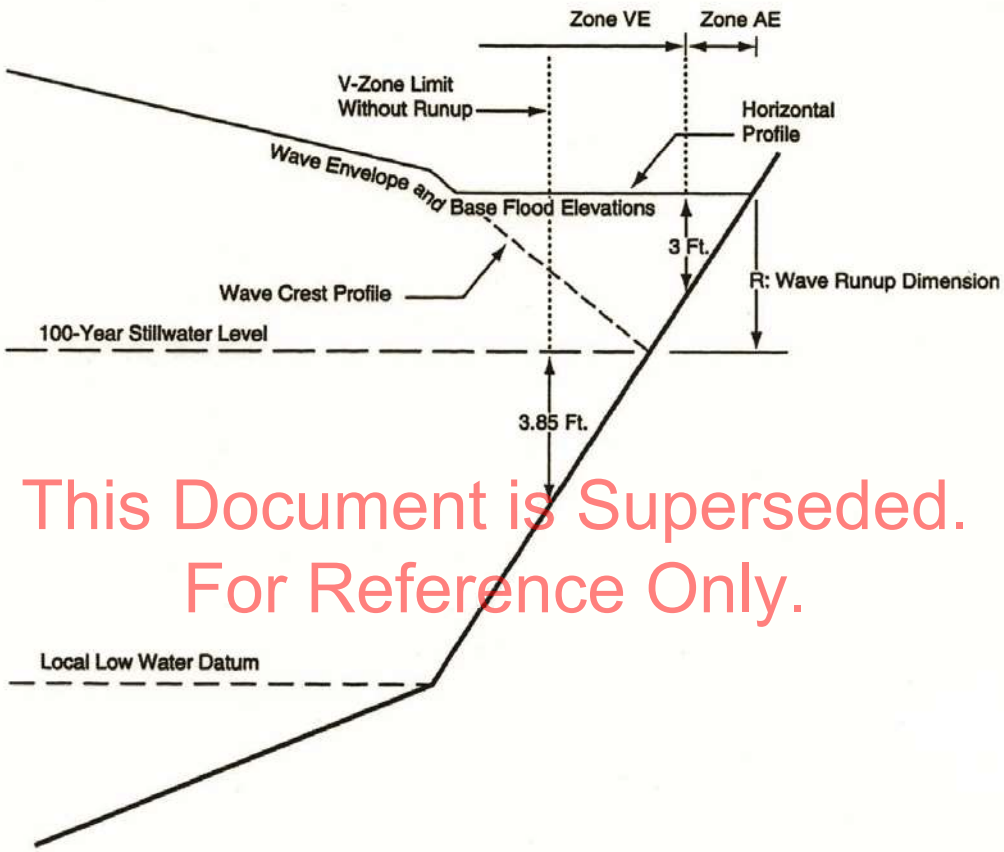


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**Figure D-46. Wave Envelope Resulting from Combination of Nearshore Crest Elevations and Shore Runup Elevation.**

The first step in identifying the flood insurance risk zones on the transect is locating the inland extent of the VE Zone, also known as the VE/AE boundary. Once the Mapping Partner has identified the VE Zone limits for each of the three criteria described above, the Mapping Partner shall place the VE/AE boundary at the location that is furthest landward. The AE Zone will extend from the VE Zone limit to the inland limit of the 1-percent-annual-chance flood inundation, which is a ground elevation equal to the representative runup elevation, or the 1-percent-annual-chance SWEL if runup is negligible or not included in the wave analyses. Additional areas of shallow flooding or ponding for the 1-percent-annual-chance flood event can be designated as Zone AH or Zone AO. All areas above the 1-percent-annual-chance flood inundation are Zone X.

The Mapping Partner shall then subdivide the AE and VE Zones into elevation zones with whole-foot BFEs assigned. Ideally, to help in floodplain management and insurance determinations for buildings and property, the Mapping Partner shall establish an elevation zone for every BFE in the wave envelope. However, the FIRM scale may limit the number of zones that can be mapped. For the FIRM to be legible, there must be a minimum width for the zones. For coastal areas, the minimum zone width is 0.2 inch. For identifying elevation zones on the transect, the minimum width is 0.2 times the final FIRM scale; for example, 80 feet for a FIRM at a scale of 1 inch equals 400 feet, 100 feet for a FIRM at a scale of 1 inch equals 500 feet.

The Mapping Partner shall not subdivide the horizontal runup portion of the wave envelope, if any; the runup elevation, rounded to the nearest whole foot, is the BFE. However, the Mapping Partner shall subdivide the WHAFIS wave crest profile. Generally, the VE Zone is subdivided first. Initially, the Mapping Partner shall mark the location of all the elevation zone boundaries on the transect. Because whole-foot BFEs are being used, these must always be at the location of the half-foot elevation on the envelope.

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The Mapping Partner shall combine elevation zones that do not meet the minimum width criterion with an adjacent zone or zones to yield an elevation zone that is wider than the minimum. The BFE for this combined zone is a weighted average of the combined zones. Often in subdividing VE Zones, the maximum BFE is located just inside the mapped shoreline, and the remainder of the VE Zone is then subdivided into minimum width elevation zones.

The Mapping Partner shall subdivide the AE Zone, if it is wide enough, in the same manner. If the total AE Zone is less than the minimum width, the lowest elevation VE Zone is usually assigned to that area. This situation typically occurs for steep or rapidly rising ground profiles, and it is not unreasonable to designate the entire inundated area as a VE Zone.

Relatively low areas inland of the AE Zone may be subject to shallow flooding or ponding of flood water and designated as AH or AO Zone. Such designations can be relatively common landward of coastal structures and dunes, where wave overtopping occurs.

Identifying appropriate zones and elevations may require particular care for dunes, given that the entire primary frontal dune is defined as Coastal High Hazard Area. Although the analyses may have determined a dune will not completely erode and wave action should stop at the retreated

duneface with only overtopping possibly propagating inland, the entire dune is still designated as a VE Zone. The BFE at the duneface is assigned for the remainder of the dune.

It may seem unusual to use a BFE that is lower than the ground elevation, although this is actually fairly common. Most of the BFEs for areas where the dune was assumed to be eroded are also below existing ground elevations. In these cases, it is the VE Zone designation that is most important to the NFIP; current regulations require structures to be built on pilings and prohibit alterations to the dune.

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### D.3.7.3 Mapping Procedures

The final work maps prepared from the results of the coastal FIS or map revision request will be used to produce a new or revised FIRM for the affected community. The work map is essentially the base map selected for the study area, as described in Subsection D.3.2, and the depiction and delineation of the coastal flood hazards that reflect the results of the wave elevation determinations and flood zones established for each respective area. The Mapping Partner shall seta the work map up with contour lines, buildings, structures, vegetation, and transects used in the wave analyses clearly and accurately located.

The Mapping Partner shall transfer the flood zones and wave elevations identified on the transects to the work maps and interpolate the boundaries between the transects. The interpolation of the results at the transects and between the transects for the results of the wave height and wave runup analyses involves judgment and skill in reading the topographic and land cover information shown on the work maps. The time and effort put forth to determine the wave elevations will be negated if the results cannot be properly delineated on the work maps and shown on the FIRM. Because roads are the only fixed physical features shown on the FIRM, it is very important that other features and the flood zone boundaries are properly located on the work maps in relation to the centerline of the roads as they will appear on the FIRM. Other important considerations for mapping the results of the coastal FIS or map revision request discussed below include shoreline fluctuations, flood zone widths, interpolation of the transitions between zones for the represented transects, and the depiction and delineation of the Zone X shaded special flood hazard areas in areas subject to wave runup hazard.

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An important but potentially ambiguous map feature is the depicted shoreline in the study area. Great Lakes shorelines are subject to large position changes, given shore erosion or accretion along with the considerable range in mean lake levels. The shoreline location may vary among the transects analyzed because of historical erosion or accretion not shown or accounted for on existing maps, but some clearly designated shoreline should be used for the work maps. For Great Lakes studies, the Mapping Partner shall ensure the depicted shoreline corresponds to the land intercept of Low Water Datum, as given in Table D-12 and usually shown on USGS maps. (It is customary to delineate flood zones only landward of the shoreline.)

The Mapping Partner shall transfer the identified elevation zones for each transect to the work maps, locating the boundaries along the transect line so that boundary lines can be interpolated

between transects, assuring that the boundaries are marked at the correct location. Because of the erosion assumptions, the location of the elevation 0.0 NGVD shoreline changes on the transect but not the work maps. The transect profile is used to determine the location of the zone change in relation to a physical feature, such as a ground contour, road, the back side of a row of houses, 50 feet into a vegetated area, etc. The boundary line along this feature for the area represented by that transect is then delineated.

The Mapping Partner shall check the widths of the zones being delineated carefully; if they narrow to less than 0.2 inch, they should be tapered to an end. Likewise, if an averaged elevation zone becomes much wider, it may be possible to break it into two elevation zones, both wider than 0.2 inch. Consideration of the final map scale of the FIRM to be produced from the work maps will help in determining how the zones should be combined and averaged.

One of the more difficult steps in delineating coastal flood zones and elevations is the interpolation and transition between transect results. Good judgment and an understanding of typical flooding patterns are the best tools for this job. The first step is to locate on the work maps any area of transition that is not exactly represented by either transect. The next step is to delineate the flood boundaries for each transect up to this area. Then consideration should be given to how a transition can be made across this area to connect matching zones, and still have the boundaries follow logical physical features. If there are other transects that are similar to this area, they could give an indication of flooding. Sometimes the elevation zones for the two contiguous transects are not the same; thus, some zones may have to be tapered to an end, or enlarged and divided in the transition area.

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Communities with significant flooding hazards from wave runup may have one transect representing more than one area because the areas have similar shore slopes. In this case, the different areas are identified, and the results of the typical transect delineated in each area. Transition zones may be necessary between areas with high runup elevations to avoid large differences in BFEs and to smooth the change in flood boundaries. These zones, which should be fairly short, should cover the shore segment with a slope not exactly typical of either area. The transition elevation is determined by examining runup transects with similar slopes and using good judgment. Transition zones should not be used if there is a very abrupt change in topography, such as is found at the end of a structure.

Lastly, Mapping Partner shall map the Zone X (shaded) areas. Areas below the 0.2-percent annual chance SWEL and not covered by any other flood zone are designated Zone X shaded and shown on the FIRM. Often the maximum runup elevation is higher than the 0.2-percent annual chance elevation; thus, there will be no shaded Zone X in that area. The Mapping Partner shall designate all other areas as Zone X without any shading.

These *Guidelines* were compiled to give guidance in the preparation of coastal FISs and map revision requests. The collection of accurate and representative data, the correct application of the models, the evaluation and comparison of the results to historical data, and the proper delineation of flood elevations and zones will produce a FIRM that is both technically correct and directly usable for the intended purposes.

During all steps of the study, especially the mapping, the final product and its purposes should be remembered: the FIRM is used to determine flood insurance premiums and regulate building standards.

Because flood elevations are rounded to the nearest whole foot, there is no reason for spending hours to resolve a minor elevation difference. Also, because structures or proposed structures must be located on the FIRM, an attempt should be made whenever possible to smooth the boundary lines and to follow a fixed feature such as a road. In preparing the FIS, not only must the mapped results be technically correct, but the FIRM must be easy for the local insurance agent, building inspector, or permit officer to use.

Additional criteria and submittal requirements are documented in the Certification forms for Study Contractors (SC-1) and Application/Certification form 5 (MT-2) for map revision requests.

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## D.3.8 Required Documentation

The Mapping Partner shall fully document the coastal flood hazard determination for each affected community. Because FIS Reports and FIRMs form the basis of Federal, State, and local regulatory and statutory enforcement mechanisms and are subject to administrative appeal and litigation, Mapping Partners shall ensure that all technical processes and decisions are recorded and documented. The FIS Report may not contain all the documentation that would be needed for a response in the event that the study results are questioned. Therefore, the Mapping Partner shall prepare an engineering report for each study. This report will provide detailed data needed by FEMA or the community to reconstruct or defend on technical grounds the study results. The minimum information required for the engineering report are summarized below.

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**Basic Data**.

In this section, the Mapping Partner shall include all contacts made to obtain data for the study. All basic data used must be fully referenced and, if possible, reproduced in the report. All historical flood information must be documented in this section, even if the Mapping Partner did not use the information in quantitative analyses.

**Transects**

Each transect must be plotted separately and show the erosion assessment, input data for wave models, wave envelope, and zone determination.

**Model Input and Output**

The Mapping Partner shall provide computer printout listings for input and output data for both the Wave Runup and Wave Height Models for all the transects. These listings must be keyed to the transect location map and transect plots.

**Study File**

During the course of the study, the Mapping Partner shall maintain a file containing records of all coordination, activities, and decisions. This is especially important where nonstandard approaches were used and engineering judgment played a significant role. The Mapping Partner shall ensure this file meets the requirements for a Technical Support Data Notebook as documented in Appendix M of these Guidelines.

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## D.3.9 Open Coast Flood Elevations and Wave Information

As discussed in Subsection D.3.2, the draft of "Basic Analyses of Wave Action and Erosion with Extreme Floods on Great Lakes Shores" (Dewberry & Davis, 1995) concluded from historical evidence that extreme floods were usually accompanied by the local 1/2-year wave condition on Lake Ontario, or by the 3-year wave condition on Lakes Erie, Huron, Michigan, and Superior. Examples of appropriate wave conditions derived for numerous sites on each of the Great Lakes are presented in Figures D-47 through D-56 and in Tables D-23 through D-27.

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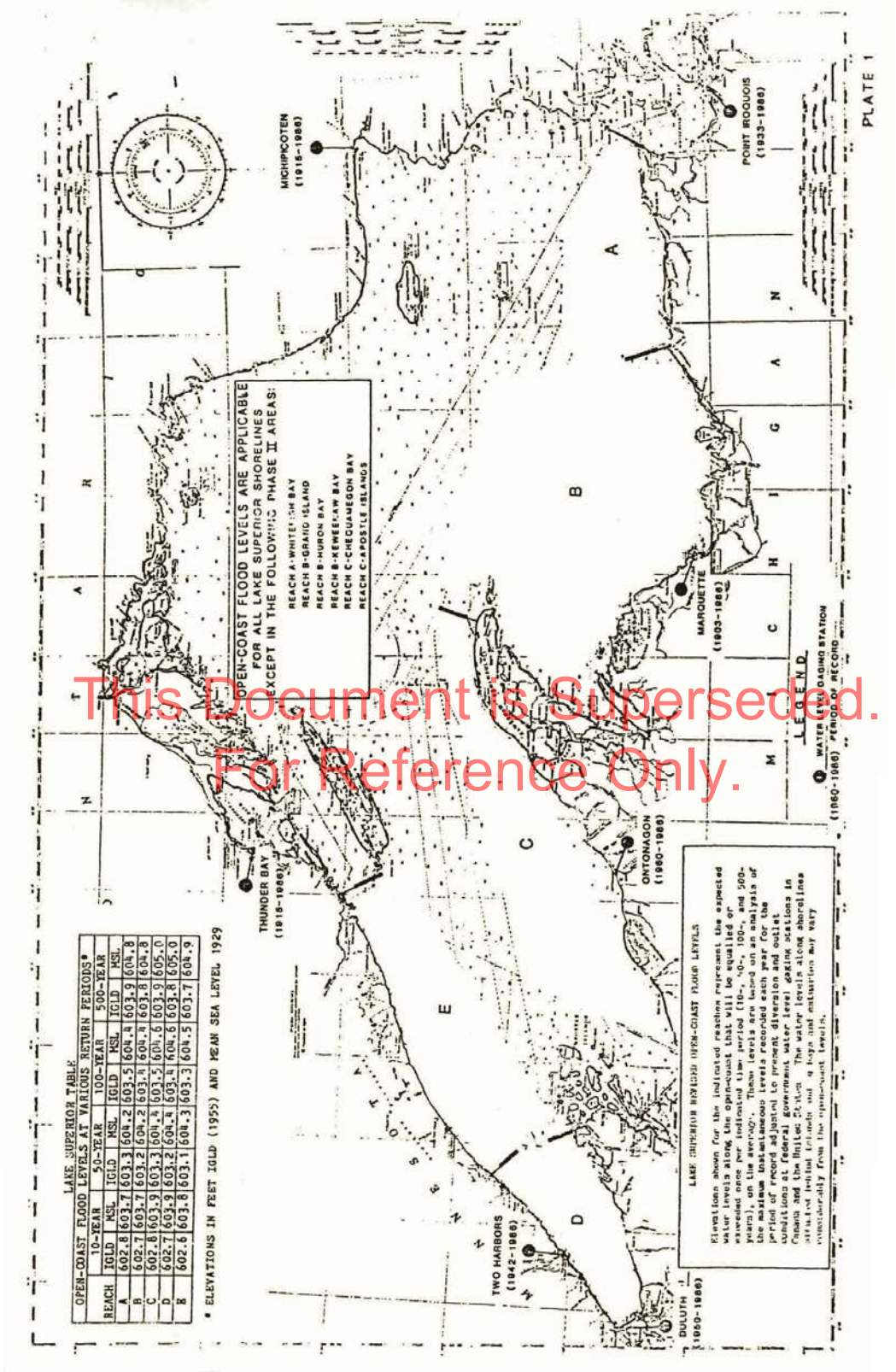


**Figure D-47. Lake Superior Table and Map of Open Coast Flood Levels (USACE, 1988).**

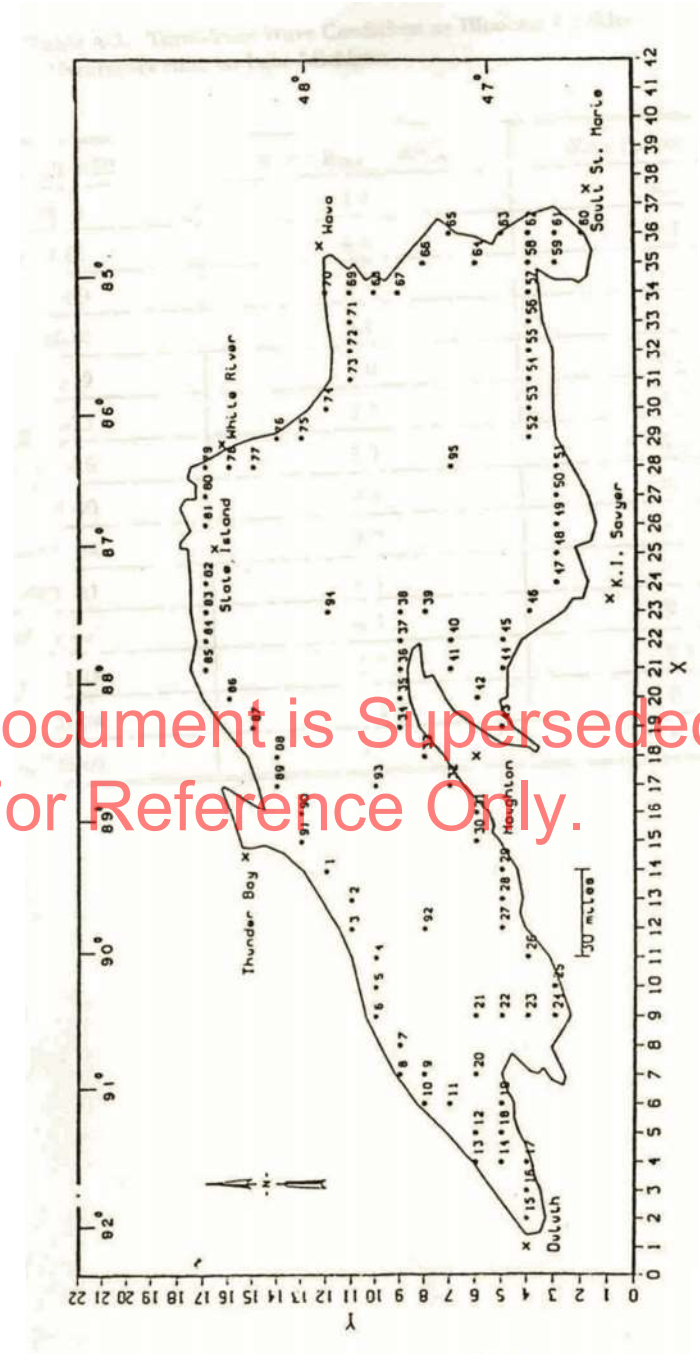


**Figure D-48. Station Location Map for Lake Superior Wave Information Stations.**

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**Table D-23. Three-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Superior**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| SUPER-05 | 6.0 | 10.0 |
| SUPER-13 | 5.8 | 10.0 |
| SUPER-15 | 3.7 | 7.1 |
| SUPER-23 | 4.3 | -- |
| SUPER-29 | 5.0 | 9.1 |
| SUPER-35 | 5.9 | -- |
| SUPER-42 | 5.2 | -- |
| SUPER-47 | 7.7 | 11.1 |
| SUPER-54 | 6.2 | -- |
| SUPER-60 | 4.5 | 7.7 |

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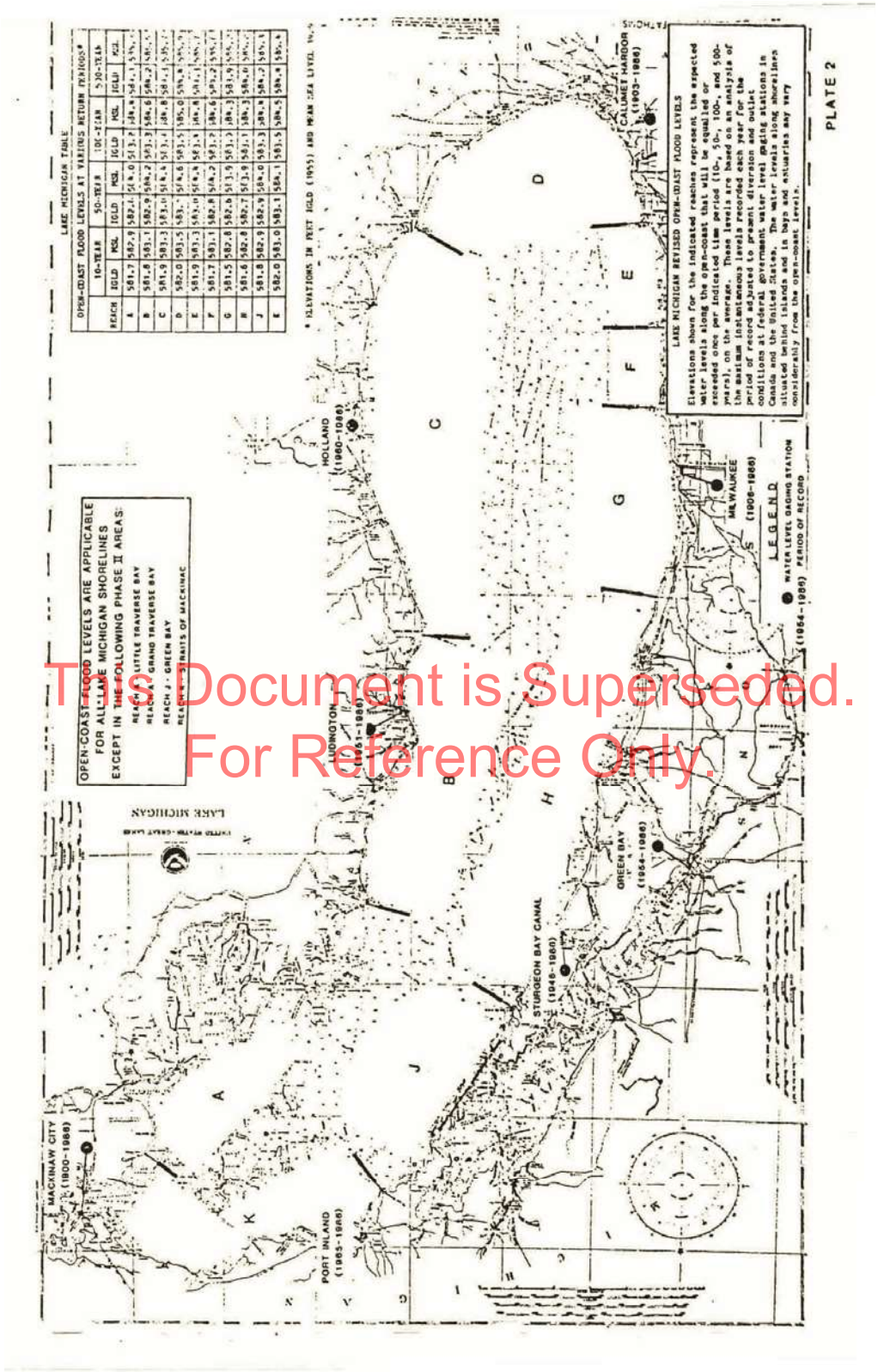


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**Figure D-49. Lake Michigan Table and Map of Open Coast Flood Levels (USACE, April 1988).**

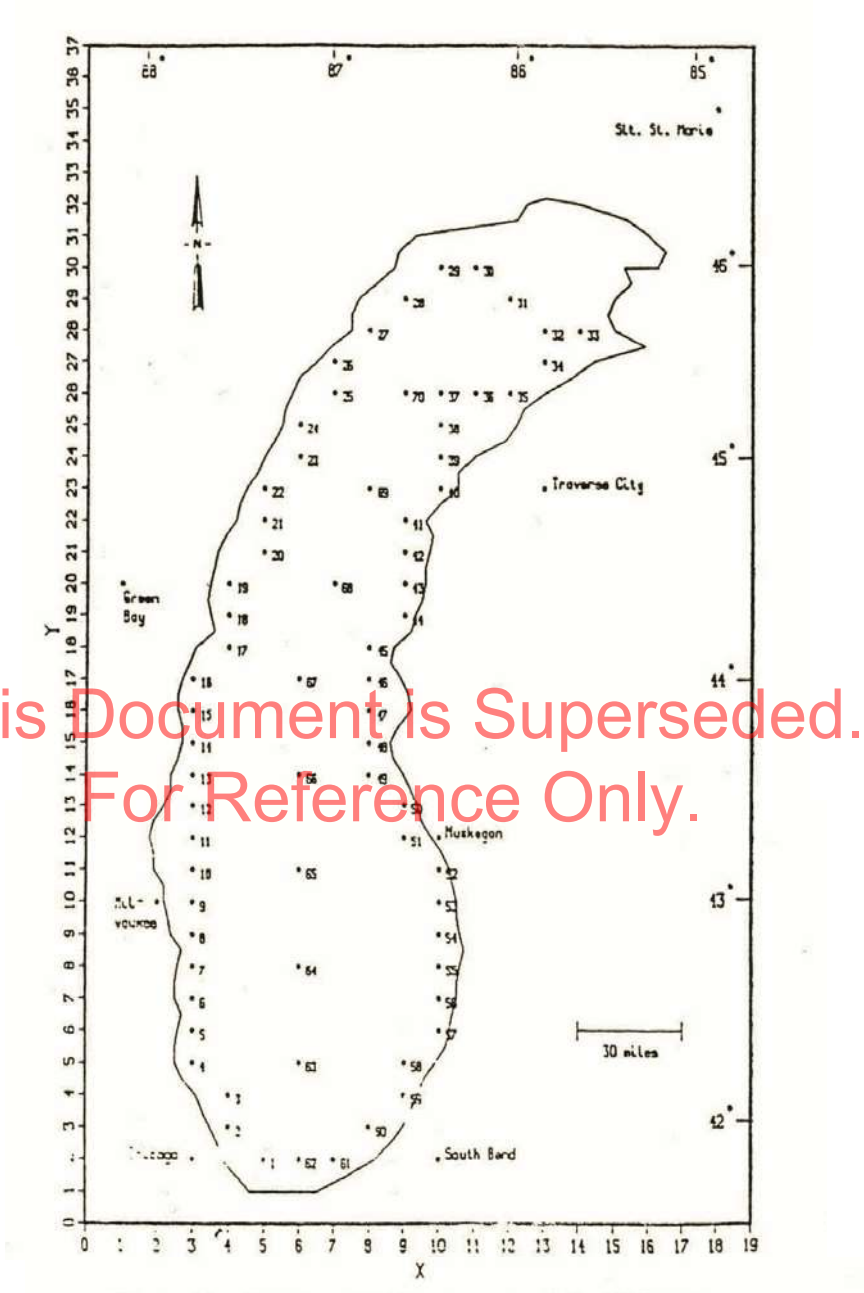


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**Figure D-50. Station Location Map for Lake Michigan Wave Information Stations.**

**Table D-24. Three-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Michigan**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| MICH-01 | 4.4 | 9.1 |
| MICH-03 | 4.6 | 9.1 |
| MICH-09 | 4.7 | 8.3 |
| MICH-14 | 3.9 | -- |
| MICH-19 | 4.0 | 8.3 |
| MICH-22 | 3.7 | 7.7 |
| MICH-26 | 3.3 | 8.3 |
| MICH-30 | 3.4 | 8.0 |
| MICH-34 | 3.7 | -- |
| MICH-41 | 4.1 | -- |
| MICH-46 | 4.7 | 9.1 |
| MICH-48 | 5.2 | 9.1 |
| MICH-54 | 5.2 | 9.1 |
| MICH-60 | 4.5 | 8.3 |

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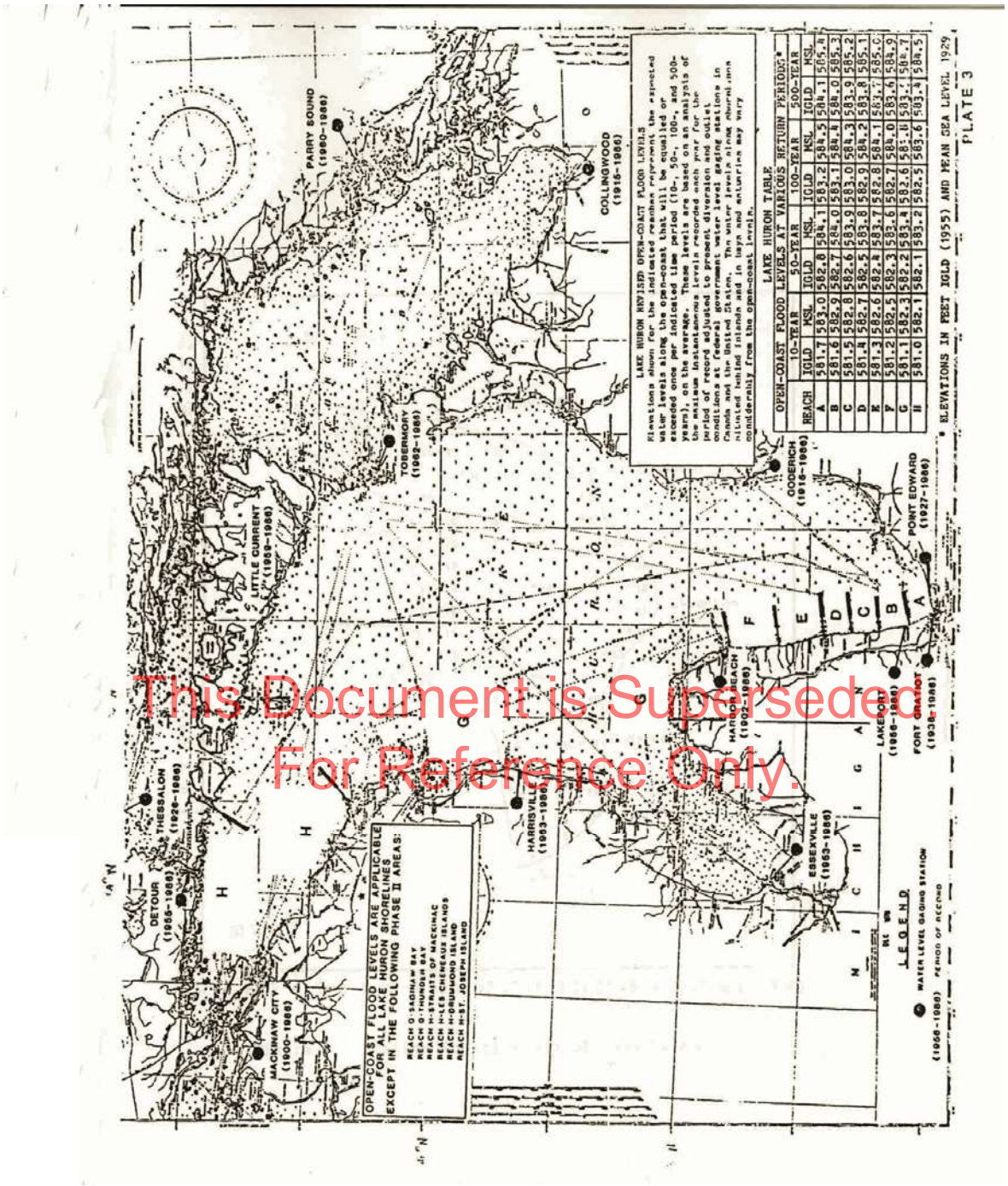


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**Figure D-51. Lake Huron Table and Map of Open Coast Flood Levels (USACE, 1988).**

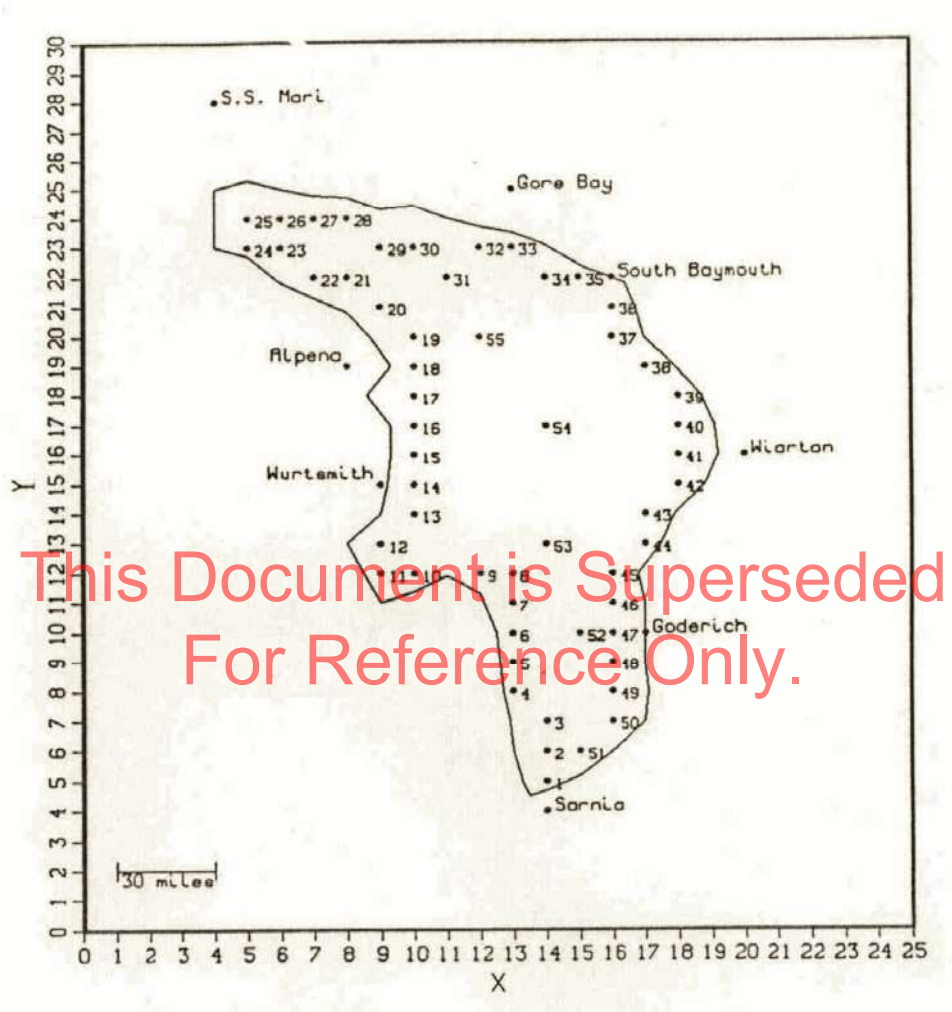


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**Figure D-52. Station Location Map for Lake Huron Wave Information Stations.**

**Table D-25. Three-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Huron**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| HURON-01 | 6.1 | 9.1 |
| HURON-02 | 6.2 | 10.0 |
| HURON-07 | 5.6 | 9.1 |
| HURON-11 | 6.3 | 9.1 |
| HURON-12 | 6.2 | 9.5 |
| HURON-15 | 6.1 | 9.1 |
| HURON-20 | 5.0 | -- |
| HURON-25 | 4.1 | 7.7 |
| HURON-26 | 4.3 | 9.1 |

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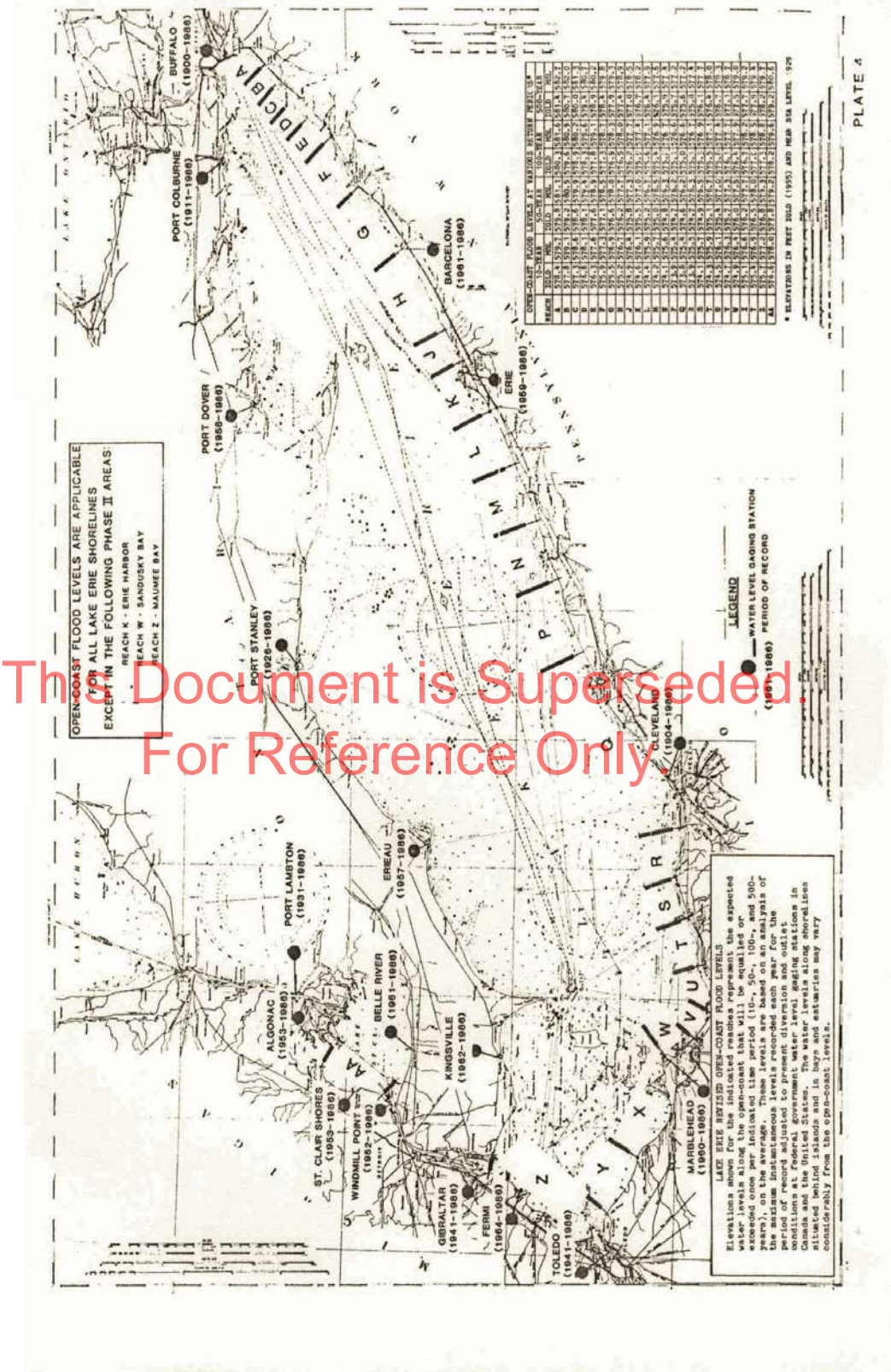


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**Figure D-53. Lake Erie Table and Map of Open Coast Flood Levels (USACE, 1988).**

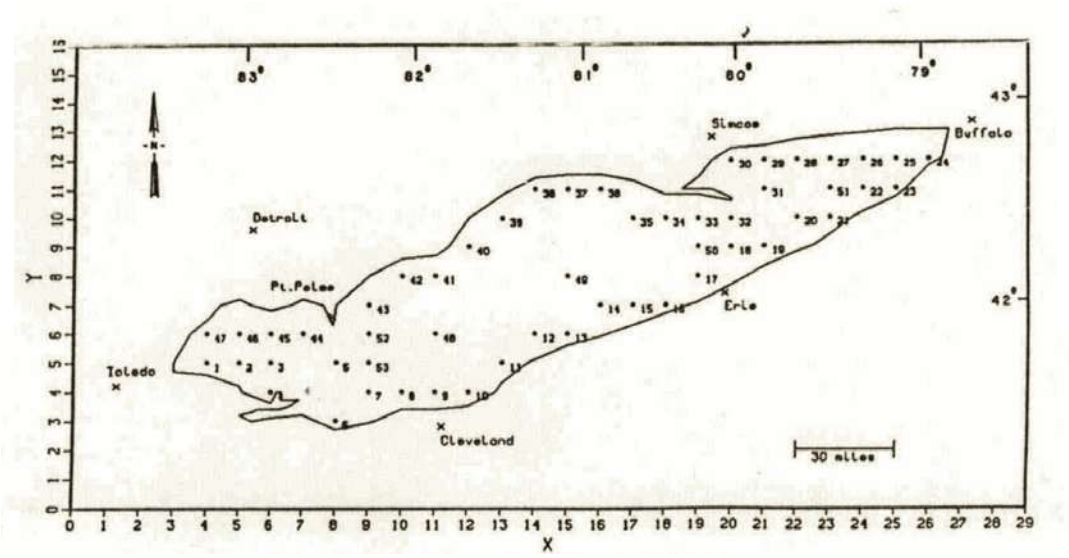


**Figure D-54. Station Location Map for Lake Erie Wave Information Stations.**

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**Table D-26. Three-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Erie**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| ERIE-01 | 2.0 | 6.2 |
| ERIE-04 | 1.9 | 6.2 |
| ERIE-07 | 3.3 | -- |
| ERIE-10 | 3.6 | 7.7 |
| ERIE-12 | 4.0 | 8.3 |
| ERIE-15 | 4.2 | -- |
| ERIE-18 | 4.6 | 9.1 |
| ERIE-21 | 4.9 | 9.1 |
| ERIE-24 | 4.2 | 9.1 |
| ERIE-47 | 1.8 | 5.6 |

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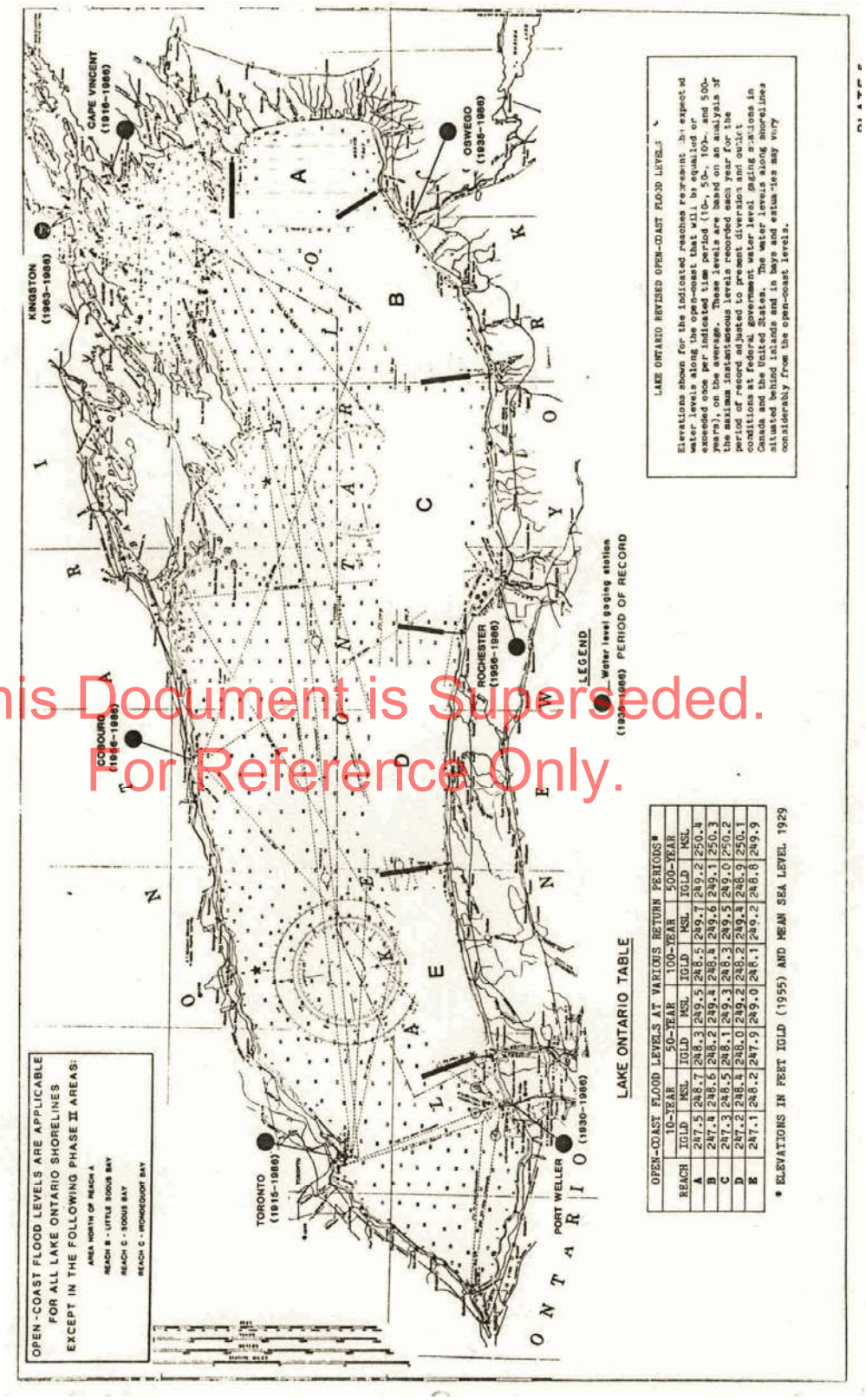


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**Figure D-55. Lake Ontario Table and Map of Open Coast Flood Levels (USACE, 1988).**

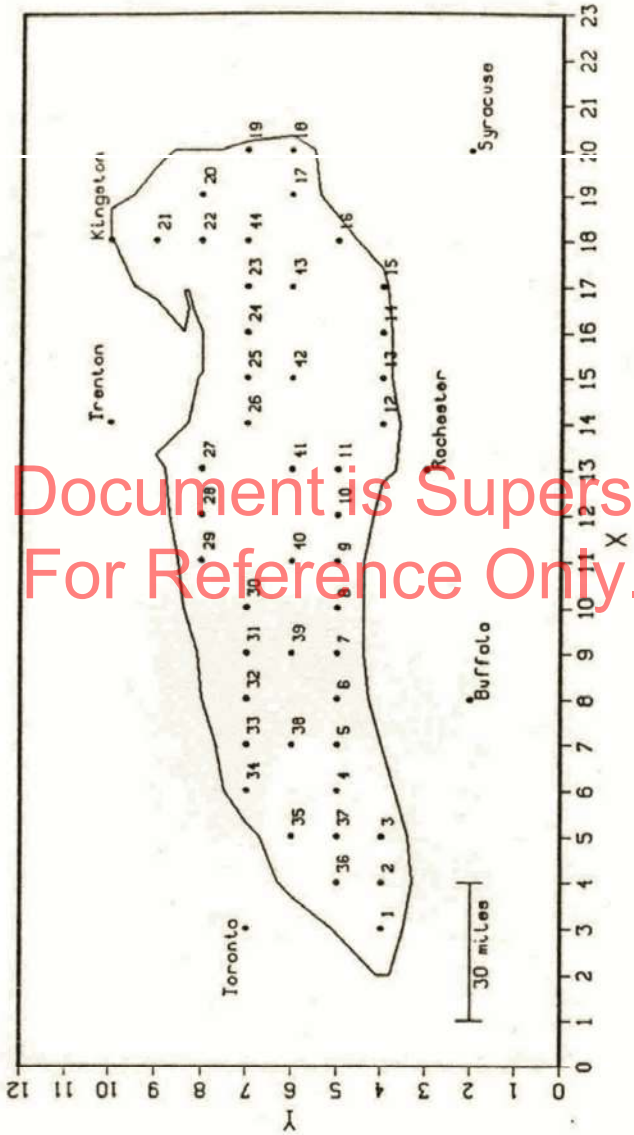


**Figure 3. Station location map of Lake Ontario**

**Figure D-56. Station Location Map for Lake Ontario Wave Information Stations.**

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**Table D-27. One-Half-Year Wave Conditions as Hindcast for Selected Nearshore Sites on Lake Ontario**

| HINDCAST SITE ID | WAVE HEIGHT (METERS) | WAVE PERIOD (SECONDS) |
|---|---|---|
| ONT-04 | 2.7 | -- |
| ONT-06 | 2.9 | 6.7 |
| ONT-07 | 3.0 | 7.1 |
| ONT-11 | 3.2 | 7.1 |
| ONT-14 | 2.6 | -- |
| ONT-17 | 3.2 | 7.1 |
| ONT-21 | 2.4 | 5.9 |

[February 2002]

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## D.4 Wave Elevation Determination and V Zone Mapping: Pacific Ocean

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

[February 2002]

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## D.5 Erosion Hazard Study, Identification, and Mapping

No FEMA guidance documents have been published for erosion hazard studies and mapping. Guidance is to be developed based on new or existing methodologies recommended by FEMA and coastal states for erosion hazard studies and mapping in all coastal areas.

[February 2002]

This Document is Superseded.
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