Guidance for Flood Risk Analysis and Mapping

Overland Wave Propagation

November 2015

FEMA

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

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

Document History

Affected Section or Subsection	Date	Description
First Publication	November 2015	Initial version of new transformed guidance. The content was derived from the Guidelines and Specifications for Flood Hazard Mapping Partners, Procedure Memoranda, and/or Operating Guidance documents. It has been reorganized and is being published separately from the standards.

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1.0 Topic Overview

During large storm surge events, surge and waves push inland from the natural coastline. The Base Flood Elevations (BFEs) in these inland areas is determined based on the storm surge (stillwater and wave setup), erosion, runup, and overland wave propagation. This guidance document focuses on the overland wave component. The overland wave heights are determined based on the stillwater elevations, starting wave conditions, ground elevation, and obstructions in the inland area. This is generally determined using FEMA's Wave Height Analysis for Flood Insurance Studies (WHAFIS) model. This guidance document focuses on the WHAFIS model input and interpretation of the results. Differences in the use of the model for different coasts are discussed.

2.0 Overland Wave Propagation Model Setup

FEMA's Wave Height Analysis for Flood Insurance Studies (WHAFIS) model has been used extensively for FEMA flood insurance studies in coastally influenced areas and is discussed throughout this guidance document. Although testing has been done with some two-dimensional models, WHAFIS is currently the only model validated for FEMA overland wave modeling projects and will be the only model discussed in this guidance document.

WHAFIS 3.0 is available at www.fema.gov/plan/prevent/fhm/dl_wfis3.shtm. Basic information on the use of the WHAFIS model can be found on FEMA's website (https://www.fema.gov/media-library/assets/documents/11563). Details specific to FEMA coastal studies for Flood Insurance Rate Maps (FIRMs) not clearly outlined in the WHAFIS User's Manual are discussed in this guidance document. The WHAFIS program is available as a stand-alone program, or as a part of FEMA's Coastal Hazard Analysis Modeling Program (CHAMP). CHAMP 2.0 is available at https://www.fema.gov/coastal-hazard-analysis-modeling-program-version-20.

2.1 Transect Placement

The WHAFIS model considers the study area by representative transects. These transects are lines generally perpendicular to the shoreline where the WHAFIS model will extract the stillwater elevations, ground elevations, and obstruction information in order to step through the model analysis of the overland wave propitiation.

Transect locations must be specified by the Mapping Partner, who must also identify topographic, vegetative, and cultural features along each transect landward of the shoreline. There are no prescriptive standards for transect spacing, but transects will usually be spaced from a few hundred feet apart (where upland characteristics are highly variable or significantly developed) to a few thousand feet apart (where upland characteristics are uniform and development is sparse). Similarly, transect spacing may need to be more closely spaced on stretches of coast with significant changes in shoreline orientation. This includes all open-coast shorelines, other shorelines along large sheltered bodies of water subject to storm surge flooding (bays, sounds, and estuaries) including the Great Lakes, and other large inland water bodies. However, damaging waves are not likely to accompany storm surge flooding along portions of small tributaries leading into large coastal bodies of water, particularly where those tributaries are narrow and winding and fetches are short. Overland transects may not be required in these instances and should be evaluated by the mapping partner. Even with relatively close spacing, transects may not be close enough to capture all the alongshore variability, and spacing transects too closely may result in irregular gutters and an increased workload, without a significant increase in map quality. However, an experienced Mapping Partner should be able to interpolate between transects using topographic, shoreline structure, land cover, and backshore development information, thereby significantly reducing the number of transects required.

Transects should be oriented in the direction that waves propagate across the 0.0-ft NGVD29 or NAVD88 (or other appropriate datum) shoreline (from water to land) during the base flood. In most instances, this results in transects approximately perpendicular to the shoreline. However, in cases where the shoreline curves or has a highly variable shape (near tidal inlets or bay mouths, or on islands, or at the ends of peninsulas and spits), waves may approach at angles that deviate significantly from the perpendicular, and some transects may be required that are not shore-perpendicular. Another consequence of curved or irregular shorelines can be crossing transects. In general, specification of crossing transects should be minimized, but some crossings may be necessary to preserve the range of possible wave approach directions in the study area. In areas where crossing transects provide conflicting modeling results, the dominate or more conservative result should be applied to mapping.

Transects used for overland wave analyses may also be used for erosion and runup analysis. Although further guidance on these topics is provided elsewhere, transect placement for combined purposed is highlighted here. In areas where wave runup might be significant, the proper location of transects is governed by variations in beach morphology (e.g., barred versus unbarred profiles, dune versus no-dune, bluff versus dune) and surf zone beach slope. On coasts with sand dunes, the Mapping Partner should site transects according to major variations in the dune geometry (e.g., dune crest elevation and the dune volume per unit length of shoreline) and the upland characteristics. In areas where dissipation of wave heights in inundated areas may be most significant in the computation of flood hazards, the Mapping Partner should base transect locations on variations in topography and land cover (i.e., buildings, vegetation, and other factors) that can influence wave transformation. The Mapping Partner may choose to site a separate transect at each flood protection structure.

Many sheltered water bodies have irregular shorelines, changing profile characteristics (e.g., wetland, beach/dune, bluff, and various armored profiles), and variable upland development patterns. These factors may dictate a reduced transect spacing (down to a few hundred feet in places) and may require many more transects than might be used along an open coast shoreline of the same overall length. It is not possible in most sheltered water flood studies to place transects close enough to capture all of the alongshore variability. However, an experienced Mapping Partner should be able to interpolate between transects using topographic, shoreline structure, land cover, and backshore development information, thereby significantly reducing the number of transects required.

Ultimately, transect specification requires a balance between representing coastal flood and severe wave conditions in developed upland areas (or other upland areas of interest) and available resources. In some cases, multiple analyses may be required and conducted; in other cases, a single analysis based on the dominant flood source and associated wave conditions may be performed. If good judgment is exercised in placing required transects, the Mapping

Partner will avoid excessive interpolation of BFEs between transects, while also avoiding unnecessary study effort.

2.2 Starting Wave and Water Level Conditions

Each transect of the WHAFIS model needs starting wave height, wave period, and stillwater elevation (SWEL) data. The Mapping Partner will have to make this determination based on wave generation and fetch conditions.

WHAFIS can compute an incident wave height at the seaward end of each transect. The WHAFIS-calculated incident wave height is based on the fetch provided by the Mapping Partner and does not take into account refraction, diffraction, or bottom dissipation effects. The Mapping Partner should perform separate wave transformation calculations if these effects will cause the incident wave height to depart markedly from the derived value generated by WHAFIS. Instead of using WHAFIS to determine the starting conditions, the Mapping Partner may leverage information from two-dimensional modeling efforts often developed as part of the development of the stillwater and wave setup results. In regards to starting wave conditions, care should be taken to determine that waves are reliably coming onshore for the chosen starting location whether the wave data is coming from two-dimensional models or the internal WHAFIS calculations. Guidance is not available on this topic, but Best Practices including “Best Practices To Determine Starting Wave Conditions of WHAFIS (1D) from 2D Simulations”, “Extracting Starting Wave Conditions for WHAFIS from ADCIRC SWAN Simulations (Region 2)”, “Starting Wave Conditions for WHAFIS when Peak Waves and Surge are not Coincident (Region 9)” area available on FEMA’s Knowledge Sharing Site.

In many instances, wave heights (from other models or other sources) are provided as the significant wave height (H_s). However, WHAFIS requires controlling wave height (H_c) WHAFIS is being used within CHAMP, the program will automatically perform the conversion of H_s to H_c. If the user needs to make the conversion outside the program, for NFIP purposes, H_c is taken to be 1.6 times H_s.

2.2.1 Atlantic and Gulf of Mexico Coasts

On open coast Atlantic and Gulf shorelines, the typical procedure is to specify the base (1-percent-annual-chance) SWEL (including wave setup) and the H_c at the transect start. With more detailed storm surge studies, a spatially varying SWEL may be applied along the transect. It is generally assumed that the maximum waves occur simultaneously with the maximum surge on the open coasts; however, the Mapping Partner must research available data to determine the appropriate wave conditions to pair with the 1-percent-annual-chance SWEL elevation.

2.2.2 Great Lakes Coasts

For the Great Lakes coastal areas, the peak water level and peak wave conditions may not occur at the same time. Therefore, the recommended approach for evaluating overland wave propagation hazards with WHAFIS in the Great Lakes utilizes the joint probability method to compute the combination of wave and water-level conditions near the shoreline that are expected to generate the 1-percent-annual chance flood conditions. This method assumes that robust wave and water level data are available from hindcast modeling. The method involves first calculating the 1-percent-annual-chance-exceedance wave crest elevation based on a statistical analysis of the maximum wave crest elevations for all storms in the composite storm set. The same is done for the stillwater levels. Then a set of effective waves and water levels is defined that creates a 1-percent-annual-chance wave crest elevation for the 1-percent-annual-chance stillwater level, and that effective wave is transformed across the transect in order to facilitate mapping. Each set of wave heights and water levels will also need an erosion analysis performed to determine the input profile for WHAFIS.

The goal of the event-based approach is to use joint probability distributions in order to compute the limiting state that corresponds to the 1-percent wave crest elevation. The Mapping Partners can choose from a number of methods to compute the critical combination of parameters that generate the 1-percent wave crest elevation.

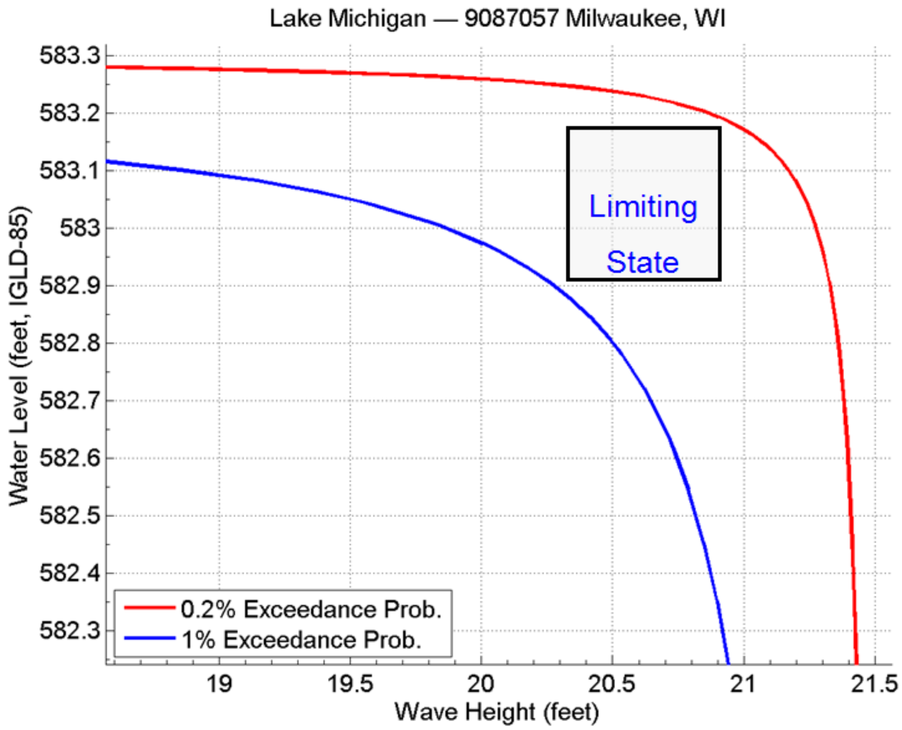
The recommended method is a simpler joint probability approach (Nadal-Caraballo et al., 2012) that closely resembles the traditional event-based approach used in Flood Risk Projects and is as follows:

For wave and water-level model results just outside the surf zone:

- Compute the marginal probability distributions of wave height (H_{m0}), wave period (T_p), and stillwater level (*SWL*).
- Using a bivariate distribution model, compute the joint probability surfaces between wave height and wave period, and between wave height and water level, respectively.
- From the joint probability surface for water level and wave height, compute the iso-probability curve corresponding to the 1-percent joint exceedance probability (see Figure 1).
- Compute at least three parameter combinations along the iso-probability curve: maximum water level and associated wave height, maximum wave height and associated water level, and at least one combination with intermediate values.
- From the water-level marginal distribution, compute the 1-percent annual exceedance water level and the expected value of wave height, E(H_{m0}) from the conditional probability distribution.
- From the wave height marginal distribution, compute the 1-percent annual exceedance wave height and the expected value of water level, E(*SWL*), from the conditional probability distribution.
- For all wave heights, compute the associated wave period as the expected value, E(Tp), from the conditional probability distribution between wave height and wave period.
- Review resultant water-level and wave condition pairings and evaluate whether any pairing can be eliminated to reduce the number of WHAFIS runs necessary. Bases for eliminating pairings include approximate duplication of another pairing, a water level that does not inundate the profile, or some other situation that can be determined a priori to not produce the most hazardous overland wave hazard among the pairings.
- Compute the eroded profile for the five or more statistical conditions from the previous steps.

- Determine the WHAFIS input for the multiple wave, water level, conditions and eroded profile from step 1. This would typically require running a 1-D surf zone dynamics model to some point near the shoreline for all cases.
- Run WHAFIS for all conditions and determine the limiting state that results in the 1-percent annual exceedance flood elevation.

Figure 1. Example of iso-probability curves corresponding to 1- and 0.2-percent annual exceedance probabilities, respectively



In deepwater, H_{m0} is approximately the same as significant wave height (H_s), but in shallow water, H_{m0} is 10 to 15 percent smaller than the H_s. This difference in wave height definition must be accounted for where necessary.

2.2.3 Pacific Coasts

Although overland waves are not always the dominant forces on the Pacific Coast, if the Mapping Partners wish to determine wave attenuation for gently sloping areas, WHAFIS may be used. However, to use WHAFIS for studies along the Pacific Coast, a different wind speed may be needed other than the defaults, which represent the 1-percent-annual-chance hurricane conditions for the Atlantic and Gulf Coasts. The default WHAFIS wind speeds are not accessible to the user but are hardwired into the program code. Consequently, a generalized version of WHAFIS for Pacific applications was developed, called PWHAFIS (Pacific WHAFIS), allowing the user to override the default speeds.

2.2.4 Sheltered Waters

Along some sheltered water shorelines, locally-onshore waves may not occur in coincidence with the onshore winds, and the maximum crest elevation may not occur precisely at the time of peak stillwater level. The Mapping Partner should perform a review of computed combinations of water levels and wave heights to find the condition approximating maximum crest elevation. Unless this review indicates coincidence of the highest water level and highest wave height is unlikely to occur, it is recommended that the Mapping Partner assume that it does occur. It may also be important to determine the direction of waves at the time of maximum surge. Some Best Practices associated with this topic have been developed and are referenced in the main body of Section 2.2.

2.3 WHAFIS Input Coding

The WHAFIS program works by dividing each transect into 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 should subdivide the fetches at points where the ground elevation changes abruptly, in the transition area of changing SWELs, and in areas with changing obstructions. The Mapping Partner should subdivide obstructions into smaller segments at the transect's seaward edge to model the wave dissipation more accurately.

The Mapping Partner should enter the necessary data using different line types, each describing a certain type of fetch or obstruction, are listed as follows:

- The Initial Elevation (IE) line describes the initial overwater fetch and the initial SWELs.
- The Inland Fetch (IF) and Overwater Fetch (OF) lines define the endpoint stationing and the 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 or other natural or manmade elongated barriers (DU line), or areas where the ground elevation is greater than the base SWEL (AS line).
- The End of Transect (ET) line requires 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 10 numeric fields describing the parameters.

To ensure proper modeling, the Mapping Partner should enter all segments of each transect either as fetches or obstructions, with one input line used 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 should right-justify the numbers in any data field only if no decimal point is used. Decimal points are permitted but not required. The endpoint 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 endpoint. 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 endpoint 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 line. It is used to begin a transect at the shoreline and to 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 endpoint of initial overwater fetch, in feet (zero at beginning of transect)
2	9-16	Ground elevation at endpoint 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.

Data Field	Columns	Contents of Data Fields
8-10	57-80	Not used

AS Line (Above Surge)

This line is used to identify the endpoint of an area with a ground elevation greater than the 1-percent-annual-chance SWEL (such as a high dune or other 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 inland side may differ from the 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 endpoint, in feet, of area above 1-percent-annual-chance SWEL
2	9-16	Ground elevation in feet at endpoint
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 endpoint, in feet, of group of buildings

Data Field	Columns	Contents of Data Fields
2	9-16	Ground elevation at endpoint, 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

DU Line (Dune)

This line enters information necessary to compute wave dissipation over flooded sand dunes and other natural or manmade elongated barriers (such as 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; 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 windspeed of 60 mph.

Data Field	Columns	Contents of Data Fields
0	1-2	IF
1	3-8	Stationing at endpoint of fetch, in feet
2	9-16	Ground elevation at endpoint, 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

<u>OF Line (Overwater Fetch)</u>

This line enters the parameters necessary to compute wave regeneration over large bodies of water (such as large lakes or bays) using a sustained windspeed of 80 mph. If an inland body of water is sheltered and has a depth of 10 feet or less, the IF line calling for reduced windspeed may be used.

Data Field	Columns	Contents of Data Fields
0	1-2	OF
1	3-8	Stationing at endpoint of fetch, in feet
2	9-16	Ground elevation at endpoint, 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

<u>VE Line (Vegetation)</u>

This line enters parameters necessary to compute wave dissipation due to rigid vegetation stands. See Section 2.4 for additional information on coding with the VE card.

Data Field	Columns	Contents of Data Fields
0	1-2	VE
1	3-8	Stationing at endpoint of vegetation, in feet
2	9-16	Ground elevation at endpoint, 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 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. See Section 2.4 for additional information on coding with the VH card.

Data Field	Columns	Contents of Data Fields
0	1-2	VH
1	3-8	Stationing at endpoint of marsh vegetation segment, in feet
2	9-16	Ground elevation at endpoint, in feet
3	17-24	Regp, number of the primary seacoast region for default plant parameters. See Figure D.2.7-3.
4	25-32	Wtp, weighting factor for the primary seacoast region

Data Field	Columns	Contents of Data Fields
5	33-40	Regs, number of secondary seacoast region. See Figure D.2.7-3
6	41-48	Np1, 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. See Section 2.4 for additional information on coding with the MG card including default values.

Data Field	Columns	Contents of Data Fields
0	1-2	MG
1	5-8	Marsh plant type abbreviation (see Table D.2.7-2)
2	9-16	CD, effective drag Coefficient; default value is 0.1
3	17-24	Fcov, 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	D1, base stem diameter (inches)

Data Field	Columns	Contents of Data Fields
7	49-56	D2, midstem diameter (inches)
8	57-64	D3, top stem diameter (inches)
9	65-72	CAb, ratio of the total frontal area of cylindrical part of leaves to frontal area of main stem
10	73-80	Not used

ET Line (End of Transect)

This line is required and must be the last 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

2.4 Vegetation Parameterization

The WHAFIS model includes representation of two types of vegetation: one for rigid vegetation such as trees and one for marsh grass vegetation (that is flexible and oscillates with wave action). The WHAFIS model input parameters are discussed in the sections below. Additional information on alternative ways to determine wave dissipation by vegetation for the Pacific Coast is discussed in Section 2.4.3 of this guidance document.

2.4.1 Atlantic and Gulf of Mexico Coast

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 Mapping Partner shall obtain representative values for h, D, and b from representative field surveys.

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 1. However, WHAFIS incorporates considerable basic information on eight common types of seacoast marsh plants found in the Atlantic and Gulf of Mexico coasts, and the information can be used by specifying geographical regions as shown in Figure 2.

If the site is near a regional 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 use in spatial interpolation. Climate affects the geographic range of each marsh plant type, so that some plant types are not found in all regions. Table 2 lists 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 percentage of coverage may be specified. Given this information, WHAFIS will supply default values for the other marsh plant parameters appropriate to the site.

Following the identification of the marsh plant types present, the area and fraction of coverage, F_{cov}, for each plant type must be calculated. The total area of marsh vegetation coverage is determined for each transect. 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 is recommended. If a plant type not listed in the table is used, then appropriate data must be developed for the marsh grass parameters.

Table 1. 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	Midstem 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.

Figure 2. Coastal wetland regions of Atlantic and Gulf coasts

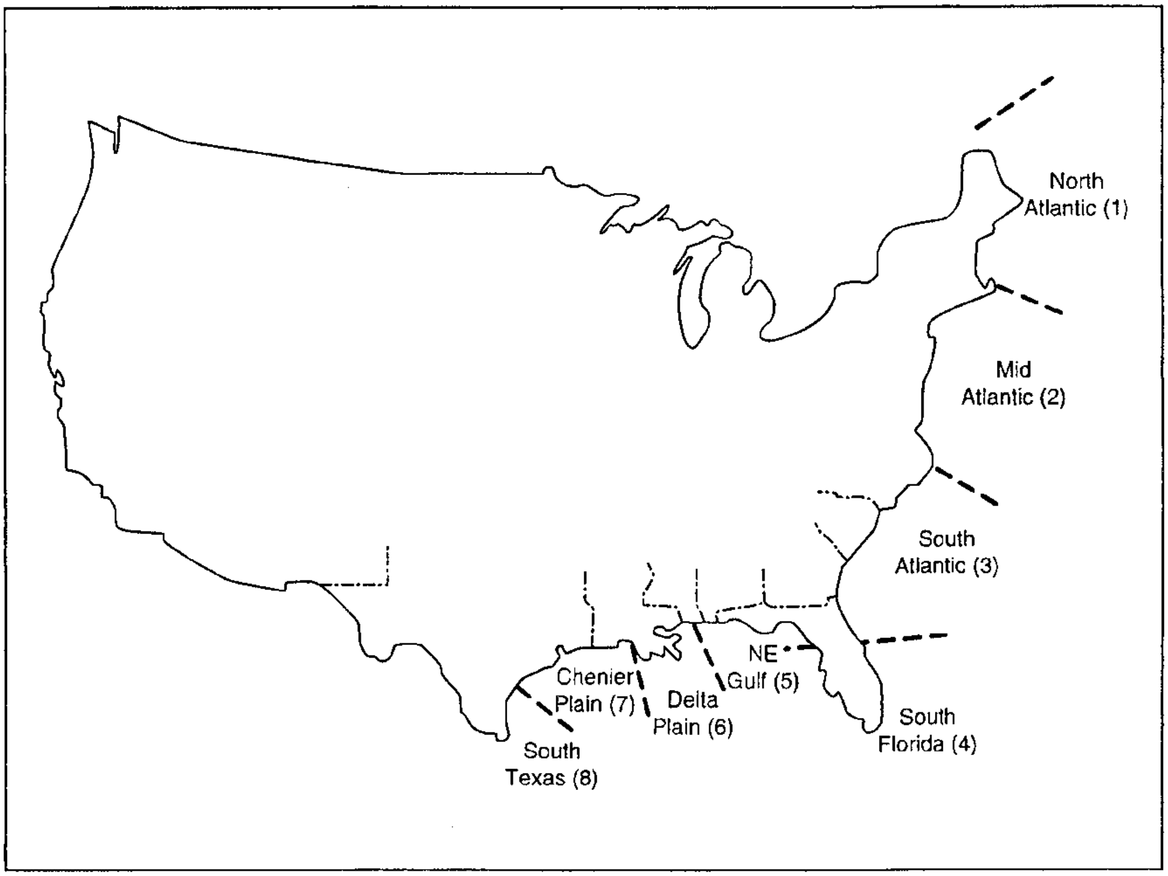


Table 2. Significant Marsh Plant Types in Each Seacoast Region and WHAFIS Default Regional Plant Parameter Data

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**
Cladium jamaicense (saw grass - CLAD)	---	---	---	7.50(+) 0.0656 6	6.00(2) 0.0260 6	---	---	---
Distichlis spicata (salt grass - DIST)	---	0.78(1) 0.0039 211	1.00(1) 0.038 243	1.00(+) 0.0038 248	--- ---	1.08(4) 0.0035 102	1.08(+) 0.0035 102	---
Juncus gerardi (balck grass - JUNM)	1.23(1) 0.0042 300	1.23(+) 0.0042 300	---	---	---	---	---	---
Juncus roemerianus (black needlerush - JUNR)	---	2.95(+) 0.0095 147	2.95(+) 0.0095 147	---	2.95(3) 0.0095 147	3.00(4) 0.0106 83	2.95(+) 0.0095 147	---
Spartina alterniflora (medium saltmeadow cordgrass - SALM)	1.39(1) 0.0184 45	1.06(1) 0.0103 36	1.63(1) 0.0141 12	1.63(+) 0.0141 12	---	1.67(4) 0.0141 21	2.62(5) 0.0211 16	---
Spartina alterniflora (tall saltmeadow cordgrass - SALT)	1.86(1) 0.0175 37	2.21(1) 0.0169 18	3.20(1) 0.0183 10	3.20(+) 0.0183 10	---	3.20(4) 0.0183 10	3.20(+) 0.0183 10	---
Spartina cynosuroides (big cordgrass – SCYN)	---	---	8.29(+) 0.0492 6	---	---	4.00(4) 0.0267 7	---	---
Spartina patens (saltmeadow grass – SPAT)	1.03(1) 0.0025 409	0.85(1) 0.0019 327	1.65(1) 0.0019 236	---	2.58(2) 0.0026 236	1.88(4) 0.0016 333	1.88(+) 0.0019 333	---

Data arranged in vertical triplets:
h, stem height below inflorescence (ft)
D, base diameter (ft)
N, number density (ft^{-1})

Parenthetical references indicate data source:
1 = Hardisky and Reimold, 1977
2 = Monte, 1983
3 = Kruczynski, Subrahmanyam, Drake, 1978
4 = Hopkinson, Gosselink, Parrondo, 1980
5 = Turner and Gosselink, 1975
+ = Extrapolated Data
--- = Insignificant amounts of plant type

2.4.2 Great Lakes Coast

For the areas of rigid vegetation located on the transect, the required input values for WHAFIS are the drag coefficient, C_D; mean wetted height, *h*; mean effective diameter, *D*; and mean horizontal spacing, *b*. The Mapping Partner should obtain representative values for *h*, *D*, and *b* from field surveys.

For the areas of flexible vegetation (i.e. marsh grass) located along the transect, regional parameters for the eight parameters used to describe the dissipational properties are not provided. The Mapping Partner may use field survey data and other research to determine representative values for C_D, F_{cov}, h, N, D_1, D_2, D_3, CA_b (see Table 1 for parameter descriptions).

2.4.3 Pacific Coast

For the Pacific Coast, overland waves are not always the dominant coastal process; frequently shorelines are dominated by wave runup. The Mapping Partner may choose not to evaluate wave dissipation; however, an analysis of overland waves may be done using WHAFIS or other dissipation calculations as discussed below.

2.4.3.1 WHAFIS for the Pacific Coast

Certain types of vegetation are common to the Atlantic Coast, Gulf Coast, and Pacific Coast regions and described in more detail in Table 3. P-WHAFIS can be used for limited Pacific Coast vegetation types that are the same or similar to those already represented in WHAFIS, but test cases are needed to verify the validity of the model for use with other Pacific Coast vegetation types.

Table 3. Common Vegetation Types on Atlantic, Gulf, and Pacific Coasts

Species	Common Name	New England	Southeast	Gulf Coast	Southern California	Northern California	Pacific Northwest
Batis maritime	Saltwort			x	x		
Distichlis spicata	Salt Grass	x			x	x	x
Scirpus americanus	Olney's Bulrush		x				x
Scirpus olneyi	Olney Three square			x		x	
Scirpus robustus	Salt Marsh Bulrush	x		x		x	
Scirpus validus	Soft Stemmed Bulrush		x	x			x
Spartina alterniflora	Smooth Cord Grass	x	x	x		x	

2.4.3.2 Other Wave Dissipation Calculations for the Pacific Coast

Besides WHAFIS, other wave dissipation calculations may be considered. If waves are propagating in the presence of an onshore wind field, enhanced dissipation shall be considered only within a scheme that allows additional wind-wave generation. This can be accomplished with wind-wave generation and transformation models. However, if the site is sheltered and wave height regeneration is unlikely, wave attenuation by sandflats, mudflats, or vegetation can be considered in an independent calculation. Initial considerations for the Mapping Partner are:

- What are the physical site characteristics?
- Is the area within the prevailing wind field?
- Are there sheltered areas where wind regeneration does not occur?
- Will the effect of the sandflat, mudflat, or vegetation be significant?

If the attenuation is deemed to be potentially significant, site-specific data, calibration, and verification may be necessary for Flood Risk Project applications.

If attenuation is significant, the following methodology can be employed to perform an initial assessment to determine if more detailed calculations are necessary. Bottom dissipation mechanisms can be mathematically expressed as a negative forcing term in the conservation of wave energy equation for steady-state, longshore uniform conditions as follows:

$$\frac{dEC_G}{dy} = -\varepsilon \qquad \text{(Eq. 1)}$$

where E is the wave energy density, C_G is the wave group velocity, ε is the energy dissipation rate per unit bottom area, and y is the direction of wave propagation. Dissipation can occur at the surface, the bottom of the water column, and within the water column due to wave breaking. One may consider ε as the sum of energy dissipations due to wave breaking and bottom and internal effects. Dissipation due to bottom and internal effects dominates in areas of non-breaking waves whereas dissipation due to breaking dominates within the breaking zone. Equations summarized in Table 4 can be used to develop an initial assessment of the magnitude of enhanced wave dissipation due to bottom effects and vegetation. If this dissipation is considered significant, the Mapping Partner may elect to use equations within these subsections to calibrate a method. Calibration could be based on pairs of measured wave heights and distances over approximately uniform depth conditions, and collected at a location similar to the study site, i.e., similar site geometry and similar wave conditions. Data used to calibrate the method shall be collected along the direction of wave propagation showing changes in wave height and period across the site. Table 4 summarizes the equations governing wave attenuation by various processes and recommends ranges of required parameters to calculate attenuation.

Wave Attenuation Due to Bottom Friction

For a rough bottom, Dean and Dalrymple (1991) express energy dissipation due to bottom friction as shown in Table 4, Equation 2. In addition to the equation for ε, this table presents the approximate range of the unknown friction factor, *f*, the equation governing attenuation, and the expression for the unknown friction factor if the wave heights at two locations are known. The variables appearing in the expressions are defined as a table footnote.

Wave Attenuation Due to Percolation

For a porous bottom, Dean and Dalrymple (1991) express energy dissipation due to bottom percolation as shown in Table 4, Equation 3.

Wave Attenuation Due to a Viscous Bottom

There are several methods for developing a preliminary estimate of wave dissipation due to viscous damping from mudflats, which are a common Pacific Coast feature within lagoons and bays.

Dean and Dalrymple (1991) and Lee (1995) express energy dissipation due to a viscous bottom as shown in Table 4, Equation 4. If the Mapping Partner determines that wave attenuation over mudflats is important, additional methods are provided in Massel (1996); however, any method to determine wave attenuation by mudflats shall be used with care. Ranges of values of ρ_2 are 3 to 4.5 slugs/ft^3 and ν_2 ranges from 0.1 to 1.0 ft^2/s.

Wave Attenuation by Vegetation

Mapping Partners working in areas where extensive marsh vegetation exists should determine if the reduction in wave height by vegetation is significant. To account for wave attenuation by vegetation, the following is required:

- Determine the initial wave height seaward of vegetation;
- Determine the distance waves will travel through marsh vegetation;
- Quantify plant characteristics, i.e., stem diameter and spacing;

- Apply plant drag coefficients (C_D = original drag coefficient approximately 1.0, C_P = plant drag coefficient approximately 5.0); and
- Calculate wave attenuation for the site in question (Table 4, Equation 5).

The Mapping Partner may choose to perform a field study to determine the amount of wave attenuation by vegetation. Relatively simple survey and data acquisition techniques can be performed to measure wave attenuation by vegetation. Using pressure sensors and/or current meters, wave characteristics in the study area can be determined. Surveying instruments can be used to characterize the site. The procedures include: installing instrumentation to measure wave heights offshore of the area with vegetation, using survey techniques to measure the distance that the waves will travel through the vegetation and site characteristics (i.e., water depth, bed slope, etc.), and measurement of plant characteristics (i.e., stem diameter, height, spacing, density). Application of field results obtained to Table 4, Equation 5 will provide guidance on the significance of wave dissipation for a particular site. If calculations predict greater than 20% reduction, the Mapping Partner shall include the effects in the Flood Risk Project. If results are not significant, the Mapping Partner may ignore attenuation by vegetation.

Table 4. Summary of Equations for Overland Propagation (Over Uniform Depth)

Wave Damping By	ε	Unknowns and Approximate Ranges	Solution for Wave Heights, H_1 and H_2, for Waves Propagating Over Distance $y_2 - y_1$	Value of Unknown For Measured Wave Heights, H_1 and H_2 Over Distance $y_2 - y_1$
Bottom Friction	$\frac{\rho f H^3 \sigma^3}{48\pi \sinh^3 kh}$	$0.04 < f < 0.16$	$\frac{H_2}{H_1} = \frac{1}{1 + \frac{f \sigma^3 H_1 (y_2 - y_1)}{12 C_G \pi \sinh^3 kh}}$	$f = \frac{(H_1 - H_2)}{H_2 H_1} \frac{12 C_G g \pi \sinh^3 kh}{(y_2 - y_1)\sigma^3}$ (Eq. 2)
Percolation	$\frac{\rho g^2 K k H^2}{8\nu \cosh^2 kh}$	$K = 3.3 D_{10\%} \pm 30\%$, $D_{10\%}$ = Diameter for Which 10% is Smaller in cm	$H_2 = H_1 e^{-A_2 (y_2 - y_1)}$, $A_2 = \frac{gKk}{2 C_G \nu \cosh^2 kh}$	$K = \frac{C_G \nu \cosh^2 kh}{(y_2 - y_1) g k} \ell n \left(\frac{H_1}{H_2} \right)$ (Eq. 3)
Muddy Bottom	$\frac{\rho_2 H^2 \sqrt{\sigma \nu_2}}{16\sigma^2} e^{2kh} (\sigma^2 - gk)^2$	$3 < \rho_2 < 4.5\, slugs / ft^3$ $0.1 < \nu_2 < 1\, ft^2 / \sec$	$H_2 = H_1 e^{-A_3 (y_2 - y_1)}$, $A_3 = \frac{\rho_2 \sqrt{\sigma \nu_2}\, gKk}{4 C_G \rho g \sigma^2} e^{2kh} (\sigma^2 - gk)^2$	$\rho_2 \sqrt{\nu_2} = \frac{2 C_G \sigma^{3/2} \rho g}{(y_2 - y_1) e^{2kh} (\sigma^2 - gk)^2} \ell n \left(\frac{H_1}{H_2} \right)$ (Eq. 4)
Vegetation	$\frac{\rho g^{3/2} C_D C_p D H^3}{12 S^2 \pi h^{1/2}}$	$2 < C_D C_p < 6$	$\frac{H_2}{H_1} = \frac{1}{1 + \frac{C_D C_p D H_1 (y_2 - y_1)}{3\pi S^2 h}}$	$C_p C_D = \frac{3\pi (H_1 - H_2) S^2 h}{H_2 H_1 D (y_2 - y_1)}$ (Eq. 5)

f = Bottom friction coefficient; σ and k = Wave angular frequency and wave number, respectively; ν and ν_2 = Water and mud kinematic viscosity, respectively; ρ and ρ_2 = Water and mud mass density, respectively; C_D and C_P = Stem and plant drag coefficients, respectively; S is plant stem spacing

2.5 Input Wind Conditions

The WHAFIS model has pre-set wind speeds for overland fetch, inland fetch cards, and marsh grass areas. The pre-set values are generally acceptable for use in the Atlantic and Gulf of Mexico Coasts. Wind velocity parameters within the currently approved model are based on Atlantic and Gulf coast storms associated with hurricane conditions. These wind speeds are too high for most Pacific Coast conditions. The Mapping Partner may need to review wind speeds and determine their applicability. The most recent version of WHAFIS allows user to specify wind speeds if defaults are not appropriate or applicable.

3.0 Model Output and Reporting

Model output standards for Overland Wave Propagation tasks are covered under the Coastal Data Capture Guidance document.

Overland Wave Propagation tasks are covered under Intermediate Data Submission Number 3. Further guidance is available in the Coastal Study Documentation and Intermediate Data Submittals Guidance document.

Additional guidance on the use of the WHAFIS model can be found in Wave Height Analysis for Flood Insurance Studies (Technical Documentation for WHAFIS Program Version 3.0) (FEMA, 1988) and Supplementary WHAFIS Documentation WHAFIS 4.0 (Divoky, 2007).