HAZUS-MH Flood Loss Estimation Methodology. I: Overview and Flood Hazard Characterization

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Abstract: Part I of this two-part paper provides an overview of the HAZUS-MH Flood Model and a discussion of its capabilities for characterizing riverine and coastal flooding hazard. Included is a discussion of the Flood Information Tool, which permits rapid analysis of a wide variety of stream discharge data and topographic mapping to determine flood-frequencies over entire floodplains. Part II reports on the damage and loss estimation capability of the Flood Model, which includes a library of more than 900 damage curves for use in estimating damage to various types of buildings and infrastructure. Based on estimated property damage, the model estimates shelter needs and direct and indirect economic losses arising from floods. Analyses for the benefits of flood warning, levees, structural elevation, and flood mapping restudies are examples of analyses that can be performed with the Flood Model.

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Introduction

HAZUS-MH is the most recent evolution of a family of natural hazards loss estimation software whose development began in the early 1990s. The purpose of HAZUS and natural hazards loss estimation software in general is to quantify the human, property, financial, and social impacts of natural hazards such as earthquake, wind, and flood, under existing conditions and given any of numerous possible mitigation measures. Quantification of losses under existing conditions is valuable for understanding and communicating the relative importance of natural hazards risks and the various factors (such as location, land use zoning, construction quality, etc.) contributing to that risk. Similarly, analysis of the beneficial impacts of mitigation measures (such as relocation, improved land use and planning, structural modifications, warning, etc.) permits informed decision making and efficient allocation of scarce resources. The first release of HAZUS, in 1997, was for analysis of earthquake effects. This paper discusses, in two parts, the development and technical details of the HAZUS Flood Model.

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Flood Model Development

Development of the HAZUS Flood Model took place in two phases that began in 1997 with the appointment of an advisory committee to provide technical oversight and guidance. Phase 1 consisted of a comprehensive review of existing flood loss estimation studies, models, and data (EQE 1998). Based on that review, a concept for a methodology was developed as represented in Fig. 1 (EQE 1999a). The concept was evaluated through proof-of-concept testing performed in six communities in regions representing various flooding conditions (EQE 1999b). The findings from the proof-of-concept testing were that:

- Discharge frequencies can be determined for all river reaches in the United States where digital elevation models (DEM) and regional regression relations are available;
- Flood depths can be determined for all river reaches in the United States where DEM and Q3 data is available. Fig. 2 is an example of the accuracy achievable using the recommended methodology and available DEM and Q3 data;
- Base flood elevations (BFEs) along coastal shore-perpendicular transects can be estimated and provide reasonable results;
- Applying U.S. Census and Dunn & Bradstreet data at the census block level provides a resolution suitable for flood loss estimation;
- Depth-damage functions for buildings developed by the Federal Insurance Administration (termed "credibility-weighted" functions) are suitable for flood loss estimation, since they are based on the best available damage data and represent more than 20 years of losses. Additionally, depth-damage functions developed by the U.S. Army Corps of Engineers (USACE) are also suitable in selected instances, for a wide variety of building types in various regions;
- Depth-damage functions for lifelines such as water, electric power, roads, and railroads can be developed using a combination of historical data, component based modeling, and expert opinion; and

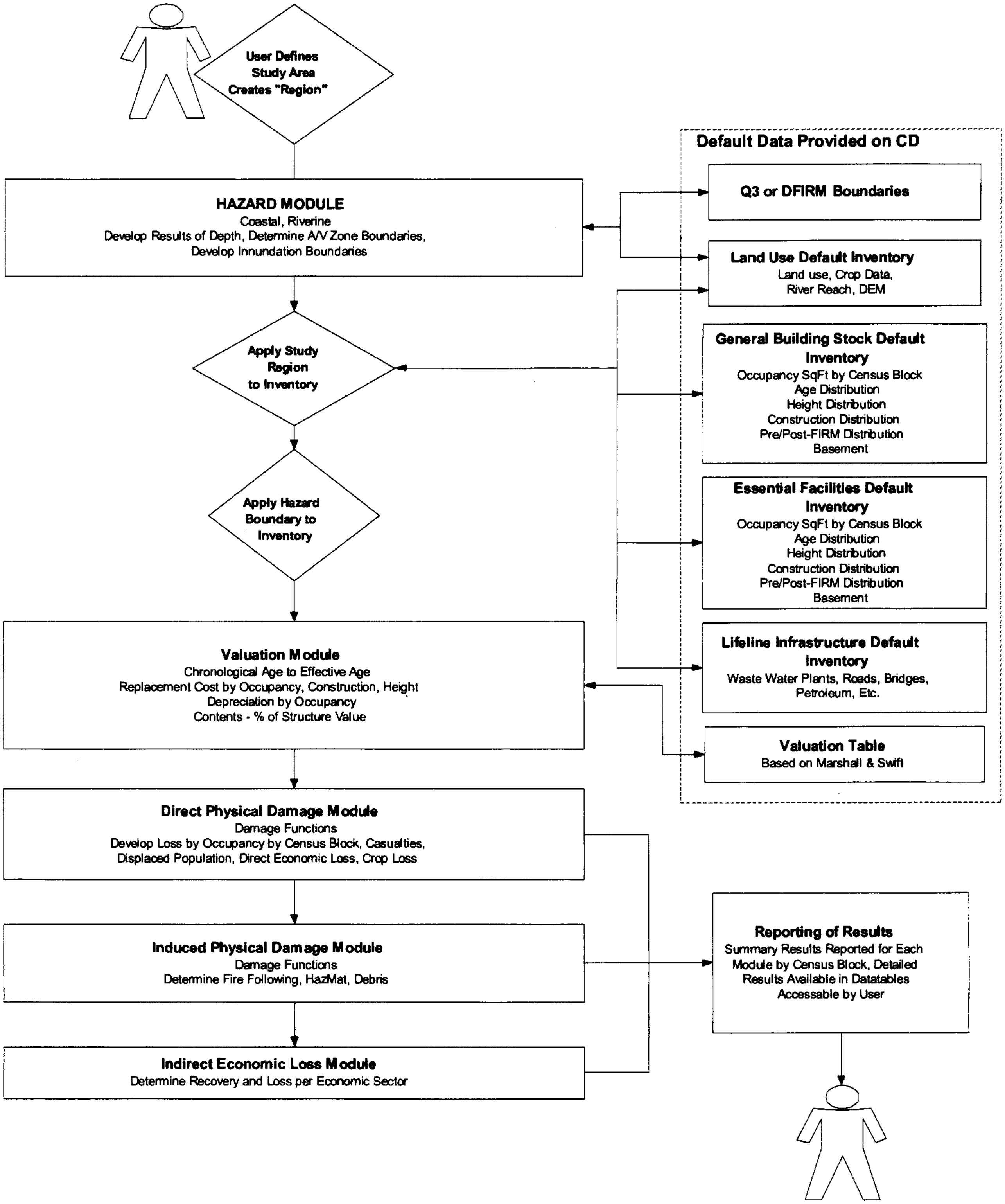

Fig. 1. Idealized flood estimation methodology and model

- The U.S. Army Corps of Engineers AGDAM model can be modified to produce reasonable results of agricultural damage.

Phase 2 began in 1999 by identifying user needs, developing the flood loss estimation methodology and associated algorithms, and acquiring and processing data needed for the Flood Model. The final step in the project was software coding and testing of the algorithms and data within a Geographic Information Systems (GIS), using a Graphical User Interface (GUI).

This paper (Part I of two parts) provides an overview of the Flood Model methodology and then details the technical basis employed in the Flood Model for characterizing riverine and coastal flood hazard. Part II (Scawthorn et al. 2006) details technical bases for flood-specific inventory aspects of the model, and direct and indirect damage aspects.

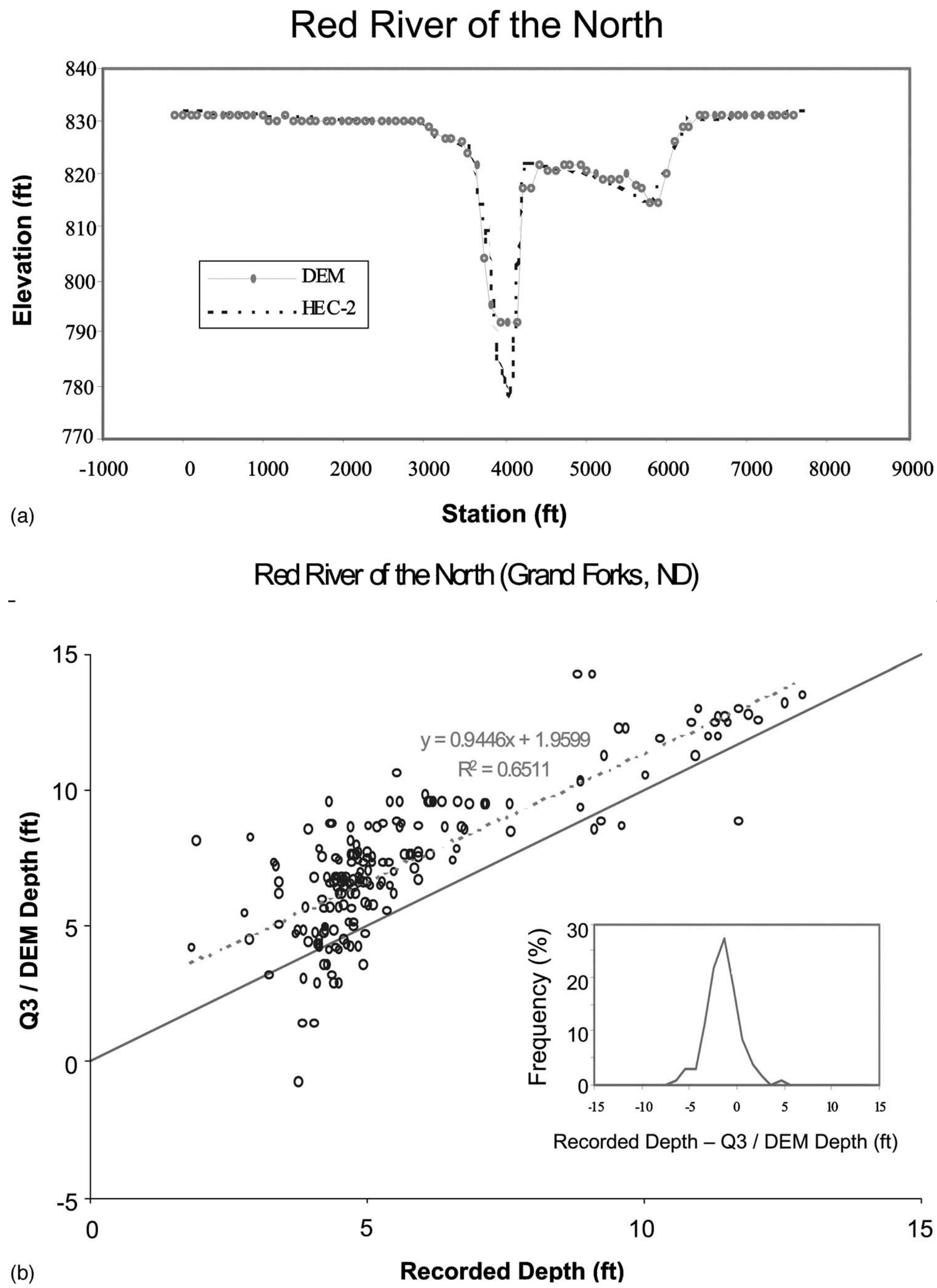

Fig. 2. (a) Stream cross sections based on USGS DEM data, compared to best available data from detailed HEC-2 analysis. (b) Scatter-plot of depth of flooding for same cross section, estimated using DEM versus actual recordings in 1997 event. Regression provides a measure of accuracy of method.

Flood Model Methodology Overview

The HAZUS Flood Model is an integrated system for identifying and quantifying flood risks and is intended to support communities in making informed decisions regarding land use and other issues in flood prone areas. It was developed for use by floodplain managers, and others, with the responsibility for protecting citizens and property from the damaging effects of floods.

Two basic analytical processes comprise the methodology: (1) flood hazard analysis (treated in this paper); and (2) flood loss estimation analysis (treated in Part II), as depicted schematically in Fig. 3. The hazard analysis portion of the model characterizes the spatial variation in flood depth and velocity in a given study area for either riverine or coastal flooding conditions. The damage and loss portion of the model estimates structural damage to buildings and infrastructure through the use of depth-damage, or vulnerability, curves. From these estimates, direct and indirect economic losses are computed and results are presented as figures, tables, and maps. Shelter needs are estimated based on the populations affected by flooding and damage to buildings, and vehicle and agricultural losses are also computed.

Depending on the degree of user expertise, the Flood Model is designed to operate at two levels. Level 1 requires minimal user interface and data, while Level 2 requires user-supplied local data for performing more detailed analyses, with the assistance of the Flood Information Tool (FIT). Users at both levels need to have

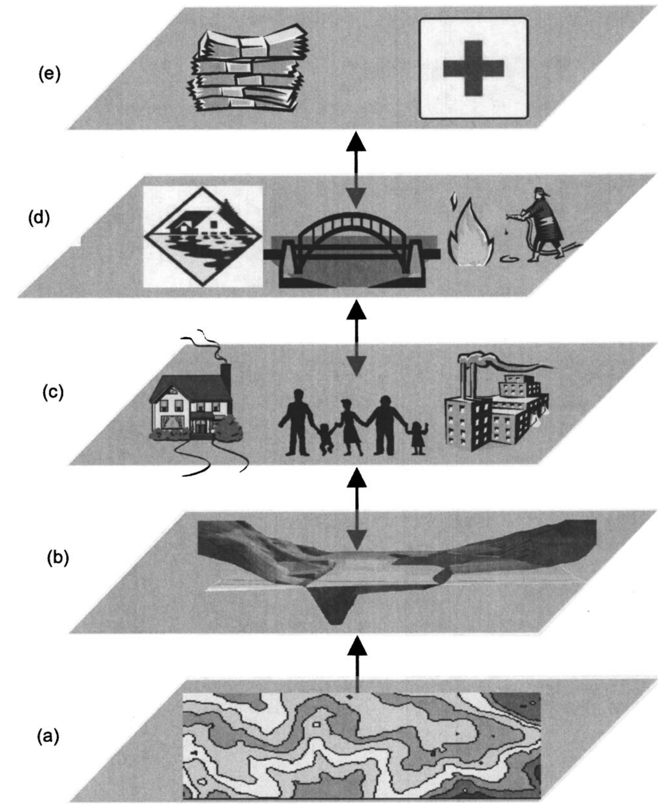

Fig. 3. Basic HAZUS flood loss estimation methodology begins with (a) digital elevation model (DEM) or equivalent topographic information. Combined with stream discharge data, (b) a flood surface elevation is derived which, relative to the DEM data, provides the areas and depth of flooding. (c) The population and properties at risk are overlaid on areas of flooding, to determine (d) damage and (e) losses.

ESRI's ArcGIS software and the Spatial Analyst extension and must supply a Digital Elevation Model (DEM) for terrain characterization. At Level 1, the DEM is imported by the Flood Model through a Web-based link to the USGS National Elevation Dataset (NED) Web site. USGS has developed the NED by merging the highest-resolution, best-quality elevation data available across the United States into a seamless raster format.

Level 1 analyses begin with a DEM or equivalent topographic information. This is combined with stream discharge and other data in a hydraulic model to determine a flood surface elevation. The difference between the ground surface and the flood surface provides the boundary and depth of flooding. Subsequent analyses are damage and loss estimation. The geographic distribution of the population, buildings and infrastructure, agricultural resources, and vehicles at risk within the flood boundary are determined from "inventory" data included with the Flood Model for the entire United States. The Flood Model uses national data on the general building stock to estimate direct physical damage to buildings and their contents, agricultural areas, and vehicles, and the resulting direct economic losses, indirect economic losses, and the exposure of essential facilities and people to flooding. Appropriate depth-damage curves are then applied to determine levels of damage. The resulting damage and loss estimates apply to all building occupancy classifications and general building types, essential facilities, crops, vehicles, and transportation lifelines (bridges only). For utility lifelines, Level 1 analysis capability is provided for potable water and wastewater treatment plants components only, but other utilities can be assessed at Level 2. Economic losses, including annualized losses, are then estimated based on physical damage to structures, including building interiors and contents. Debris generated from damaged buildings is computed, as well as shelter requirements for displaced people. The Flood Model has the capability to analyze the effect of flood warning on the degree of expected damage, and the effect of damage given flow velocity.

For Level 2 analyses, the Flood Information Tool ("FIT" tool) is used to preprocess site-specific flood hazard data and facilitate its import into the Flood Model for further analysis of damage and loss. The FIT tool has been designed to operate as an extension within *ArcGIS* and allows users to create depth grids for various return periods and other parameters. Fig. 4 shows the input data requirements for the FIT, and how the output results from the FIT are integrated into the HAZUS Flood Model. Users are required to have the following data:

- Flood surface data such as Coastal Base Flood Elevations (BFE), digital stream cross sections attributed with flood elevation, or digitized BFE lines from the Flood Insurance Rate Map (FIRM) in the form of a polyline;
- Digitized floodplain boundaries such as those shown on a FIRM and that have been digitized, a Digital Flood Insurance Rate Map (DFIRM), Q3 data, or any other floodplain map in the form of a polygon; and
- Ground elevation data in a grid format that may be built from contours, Triangulated Irregular Network (TIN), or other formats.

In Level 2, more detailed site-specific data can be employed to replace the default national datasets for buildings and other parts of the inventory. Development and importation of site-specific data are facilitated by use of the Building Inventory Tool ("BIT") and InCAST tools ⟨http://www.fema.gov/hazus/hz_meth.shtm⟩.

Flood Hazard Characterization

The starting point in analyzing potential flood losses is the quantification of the flood hazard. For Level 1 of the Flood Model, users have the capability to produce flood depth grids along any river reach or shoreline in the United States, while at Level 2 the FIT is employed to develop the grid and users are required to have greater knowledge of local flood hazards and a working knowledge of GIS. This section describes the methodology and required data for analysis of riverine flooding, with supplemental discussion of coastal aspects as appropriate.

Flood Hazard Definition

Riverine flood "magnitude" is usually measured as stream discharge, which can then be used to estimate water surface elevations, and thus depth of flooding, at various points along a stream. For example, given stream cross sections and relevant topography, a stream discharge that has a 0.01 probability of exceedance per annum can be used to calculate the elevation that has a 0.01 probability per annum of being exceeded by floodwater. Flood hazard is defined by this relationship between depth of flooding and the annual probability of inundation greater than that depth, and is depicted in a depth-frequency curve.

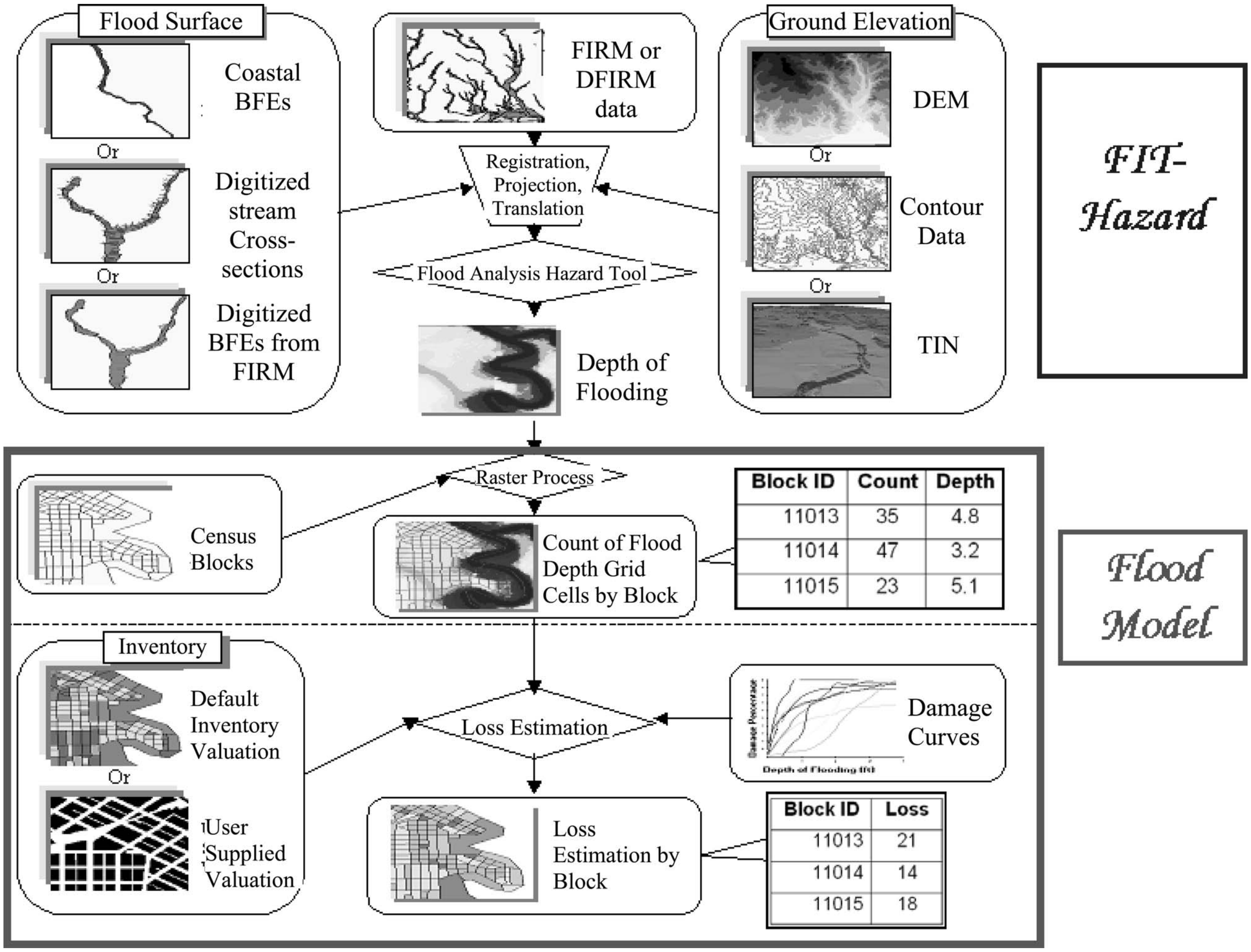

Fig. 4. Overview of integration of FIT and HAZUS-MH Flood Model

Data Requirements

Topography

Topographic data is fundamental to flood hazard analysis, and acquiring accurate, high-resolution topographic data is one of the costliest aspects of flood loss estimation. This hurdle has been significantly lowered by the availability of low cost, accurate, nationally consistent elevation data at a 30-m grid ("postings") and, increasingly, at 10-m postings, developed by the United States Geological Survey. This National Elevation Dataset (NED) can be found at ⟨http://edcnts14.cr.usgs.gov/Website/store/viewer.htm⟩ (see Fig. 5) and is available at no cost if downloaded via file transfer protocol (FTP), or for a fee if delivered on CD.

This data is used for determining topography in study areas for the Level 1 analysis. The Flood Model contains the algorithms and software for processing the data, including determining stream reaches based on topographical analysis and estimating discharge frequencies based on USGS-developed regional regressions, as described below.

Depth-Frequency Data

At Level 1, there are three sources of data from which depth—frequency information can be derived: DFIRMs, Q3 data, or by a triangular approximation method:

1. Digital Flood Insurance Rate Maps (DFIRMs) contain cross-section alignment and flood elevation information associated with the 0.01 annual probability of exceedance flood discharge value (as defined in the flood insurance study, FIS). When available, this information is used with DEMs to identify cross-section alignments, define cross-section geometry, and estimate friction slope and roughness coefficients.
2. Q3 data contain, at a minimum, the location of the 0.01 annual exceedance probability flood plain boundaries associated with a FIS. Cross sections can be "drawn" as straight line segments between the points where the cross sections shown on a Flood Insurance Rate Map (or Flood Boundary Floodway Map) cross the 0.01 annual exceedance probability flood plain boundaries. BFEs are then defined by using the DEM to determine the ground elevation at those points. Flood depths anywhere within the floodplain are determined by defining a surface using the elevations determined at each cross section, either by the DFIRM or Q3/DEM method. Subtracting the DEM ground elevations from the corresponding elevations of the surface yields the flood depth at any point within the flood plain. Within this framework, higher-level analyses utilizing more detailed DEMs and/or hydraulic modeling can be incorporated by simply registering a set of cross-section alignments and corresponding elevations with the DEM.
3. Triangular approximation may be used where the resolution of the available DEM is not good enough to define cross-section geometry. In that case, floodplain boundaries are approximated using the Q3 data and flood depths are estimated

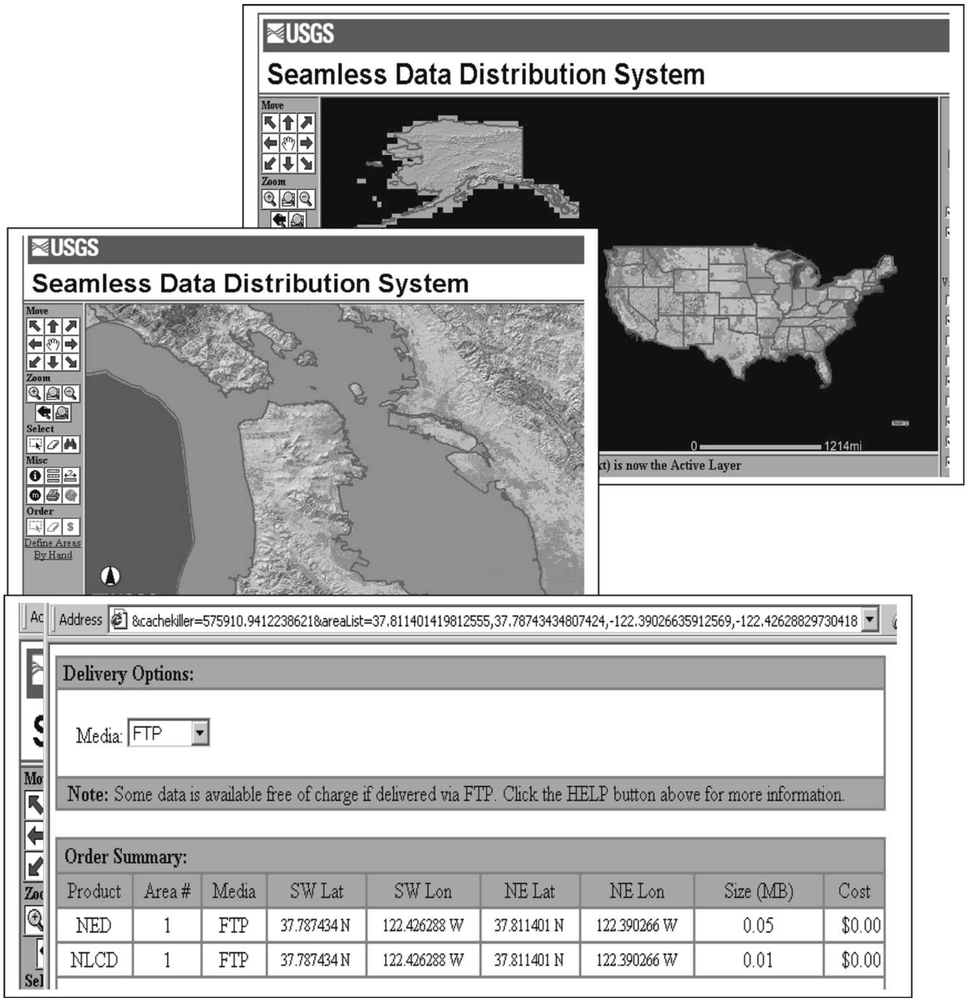

Fig. 5. National Elevation Dataset, available free from USGS ⟨http://edcnts14.cr.usgs.gov/Website/store/viewer.htm⟩

directly by assuming triangular cross-section geometry. If information regarding flood frequency and channel slope can be obtained, this method defines flood depths everywhere without first determining flood elevations by assuming a triangular geometry and an "n" value to solve Manning's equation using the Q3 data and the results of the hydrologic analysis. A DEM lacking the resolution sufficient for defining cross-section geometry (90-m postings, for example) can still be used to define drainage area boundaries, and approximate stream locations and main channel slopes.

Level One Flood Hazard Analysis

Riverine Flood Hazard

Level one hydrologic analysis is performed for points along a stream reach using regional regression equations developed by the USGS (Jennings et al. 1994). The USGS has divided each state into hydrologic regions and developed a set of regional regression equations for each region, with the following form:

$$Q_T = Cf_i(P_1)f_2(P_2)\cdots f_n(P_n) \tag{1}$$

where Q_T=discharge value with a annual probability of exceedance of $1/T$; C=constant; and $f_i(P_i)$ denotes a function of the ith parameter of the equation.

The number and types of parameters vary from one equation to another. With few exceptions, the f_I's are power functions, such as the drainage area raised to some exponent. A shape file of polygons representing hydrologic regions in the United States is included in HAZUS. For example, hydrologic regions in the vicinity of Shenandoah County, Va. are shown in Fig. 6. Tables included with the Flood Model contain the information necessary to apply the equations. There is a table for each computed annual probability of exceedance, with each record in the table associated with a region and each field associated with a function. For example, the first field in every record is the constant, C, and the second field is the exponent of the drainage area. If a region does not use a particular function, the corresponding field contains a zero. The results of applying the equations are adjusted using stream gauge data where the drainage area at the gauge is between 50 and 150% of the drainage area of the node. Discharge values for reaches on main streams are interpolated from the corresponding values in the default flood frequency database.

The hydraulic analysis uses a rating curve plotted as one or more straight lines in log-log format, with changes in slope indicating a corresponding change in ground geometry. For example, when depth reaches the top of a channel, the floodplain tends to get much wider with this increase in depth. That is, the channel is somewhat steep-sided and narrow and the floodplain is relatively flat and wide. Because flood losses occur in the floodplain and not

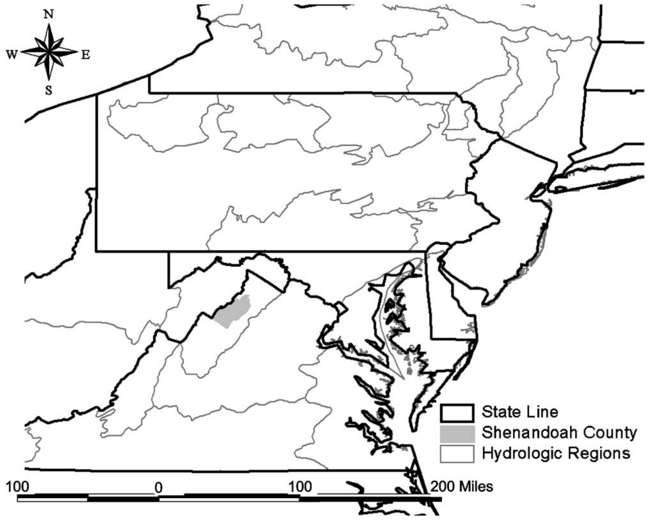

Fig. 6. Hydrologic regions near Shenandoah County, Va.

in the channel, one needs only to define the part of the rating curve for the floodplain. Since the straight line on log-log paper defines a power function, a rating curve in the floodplain can be approximated as

$$d_i = cQ_i^f \tag{2}$$

where d_i=depth; Q_i=discharge; i=index denoting frequency; and c and f=constants.

The floodplain is estimated to have a constant slope as in Fig. 7. For a given flood elevation, the distance, L_i, from the channel to the floodplain boundary (the left side of the 0.01 annual exceedance probability floodplain, for example) is proportional to depth, d_i. The reference (zero) point of that depth is a projection of the floodplain slope into the channel as shown in Fig. 7.

Denoting the left side and right side slopes of the floodplain portions of a cross section s_L and s_R, respectively, the reference (i.e., middle-of-the-channel) depth can be written as a function of the distance from channel to the floodplain boundary. Therefore the rating curve can be defined in terms of the distances from the channel to two flood boundaries. If L_i and R_i are those distances

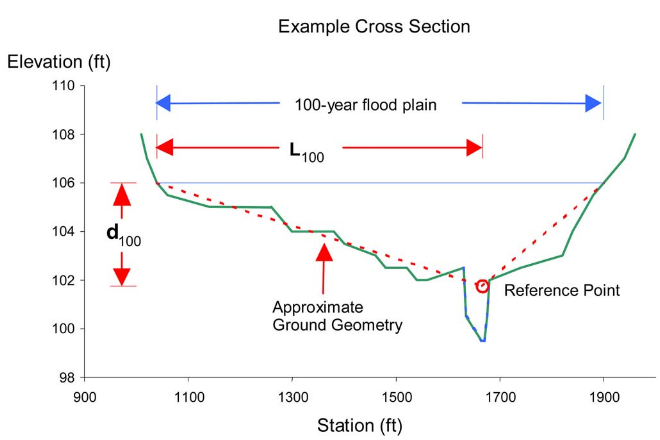

Fig. 7. Approximate floodplain geometry

$$d_i = s_L L_i = s_R R_i \tag{3}$$

Given only the width of the floodplain and assuming a triangular cross section as in Fig. 7, one can derive a rating curve, which defines a lower limit of the reference depth associated with the floodplain boundary.

The average flow velocity, v, at a given cross section of area A is the discharge value, Q, divided by A. That is, $v=Q/A$. The energy associated with a given flow, Q, through a cross section of area A is

$$E = d + \frac{v^2}{2g} \tag{4}$$

where E, called the energy head, denotes the total energy (referenced to the channel bottom). The first term on the right side of the equation, d, the depth, denotes the potential energy; and the second term, called the velocity head, denotes the kinetic energy. Velocity head equals the square of the velocity, v, divided by twice the acceleration of gravity, g.

The minimum energy associated with a particular flow at a given cross section occurs at "critical depth." Above critical depth, energy increases and the flow is said to be subcritical. Below critical depth, energy decreases and the flow is said to be supercritical. Most flood situations are subcritical and when not, flood depths are very close to critical depth. That is, flood depths are, essentially, no less than critical depth. For a triangular cross section with a top width, B, and conveying a flow, Q, critical depth, d_c, is

$$d_c = \sqrt[3]{\frac{4Q^2}{gB^2}} \tag{5}$$

The top width is the width of the floodplain or, using the convention in Fig. 7, $L+R$. If the flood-frequency curve is determined and measures the width of the 0.01 annual chance floodplain on one of FEMA's Q3 data, a lower limit for the depth associated with that floodplain may be determined and is referenced to the lowest point in the triangular approximation of the cross section. It is the minimum value of d_{100} in Fig. 7. Locating the stream relative to the floodplain boundaries allows one to determine the side slopes of the cross section. That is

$$s_L = \frac{d_{100}}{L_{100}} \tag{6}$$

and

$$s_R = \frac{d_{100}}{R_{100}} \tag{7}$$

where

$$B_{100} = L_{100} + R_{100} \tag{8}$$

Noting that

$$B = \left(\frac{s_L + s_R}{s_L s_R}\right) d \tag{9}$$

the critical depth in a triangular cross section can be written in the form of a rating curve

$$d_i = \sqrt[5]{\frac{4 s_L^2 s_R^2}{g(s_L + s_R)^2}} Q_i^{(2/5)} \tag{10}$$

Critical depth defines, essentially, a lower limit on the depth and, consequently, an upper limit on velocity. For streams where the

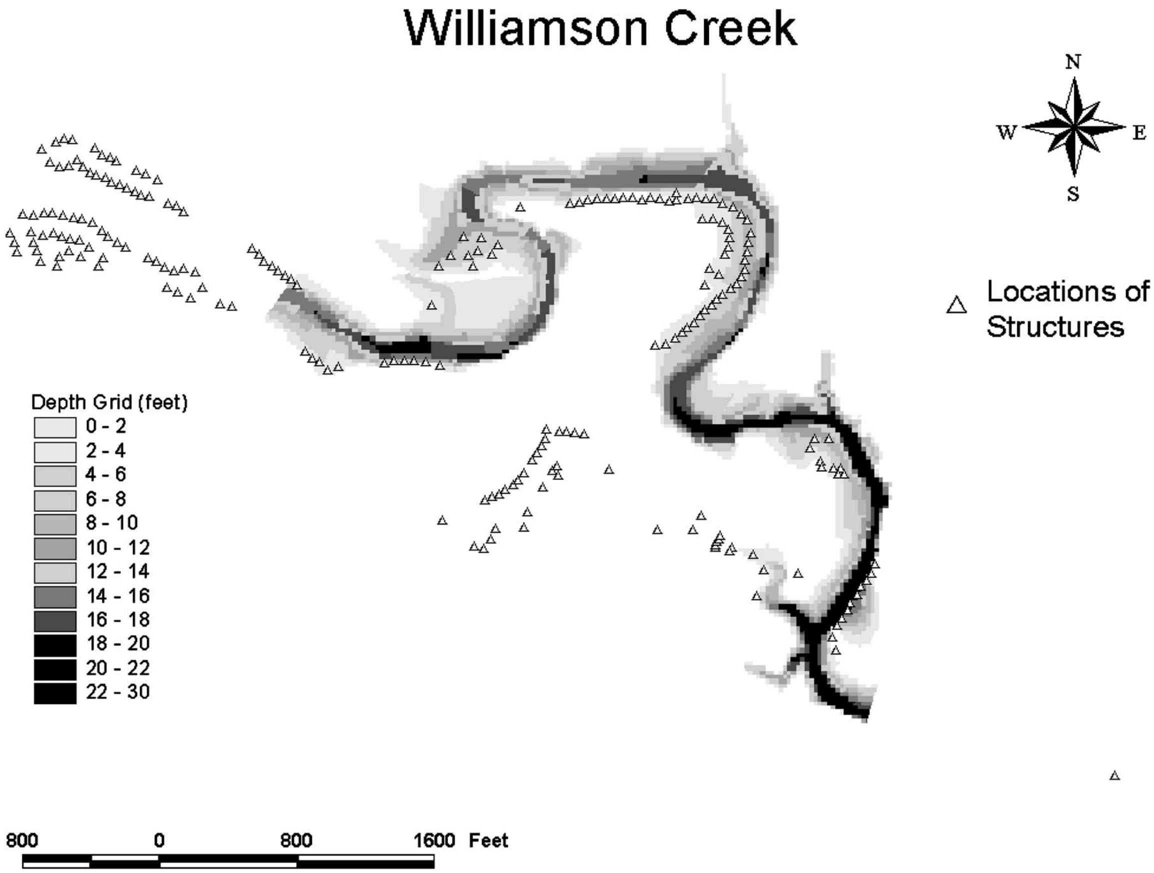

Fig. 8. Example flood depth grid and structure locations

"roughness" of the floodplain impedes the flow, velocities are less than those of flow at or near critical depth since roughness is a measure of the resistance to flow created by the ground surface and cover. For example, scattered boulders create more resistance than smooth clay surfaces; dense brush and forest create more resistance than open grasslands; and dense housing developments create more resistance than large parking lots or streamside parks.

The net result of this approach is the ability to determine the flood depth associated with any point georeferenced to the DEM. Fig. 8 shows an example grid of flood depths, together with structures, georeferenced to the DEM in and around that floodplain, which can be used to determine the number of structures in the floodplain and the depth of flooding at each of those structures. Other information readily available from the depth grid include distribution of flood depths within a city block, or the percent of cropland that might be inundated by 1 or more feet of floodwater during a specific event. The depth grid, combined with an inventory of the built environment, is used by the Flood Model to determine flood loss potential, by applying the appropriate depth-damage curves.

Velocity Effects

High velocity floodwater contributes to damage because it carries sediment and debris and affects structures by eroding soils from stream banks and from under foundations, as well as by applying lateral forces in combination with buoyant forces. The average velocity within a stream cross section is defined as the discharge at the cross section divided by the area of flow. Within a cross section, velocities are generally greater in the deeper channel areas than in shallow overbank areas. Velocities in the Flood Model are calculated as the ratio of flood depth to the average depth within a cross section, and between cross sections velocities are interpolated. Velocity grids are then created using the same irregularly spaced grid of points used to create the flood depth grids.

Although there are few velocity-specific damage curves currently available for use in the Flood Model, the spatial distribution of the estimated floodwater velocities may currently be used as supplemental hazard information, and can be used in the future for development of velocity-specific damage curves.

Coastal Flood Hazard

Coastal flood hazards (i.e., coastal flood surfaces and coastal flood depths) may be determined using two methods. Both yield a 0.01 annual probability of exceedance flood surface that serves as the basis for estimating surfaces for other return period floods using elevation ratios. These two methods are

- The first (default) method uses existing data and may be carried out by any user possessing ground surface elevations, mapped flood hazard zones, and BFEs (Fig. 9).
- The second method calculates wave crest elevations along shore-perpendicular transects. Required user inputs include a ground surface, the 0.01 annual probability of exceedance stillwater elevation from the FIS, the wave setup at the shoreline from the FIS, and the initial wave height at the shoreline also from the FIS.

The 0.01 annual probability of exceedance flood surface is the basis for all other flood surfaces. The coastal model calculates the 0.10, 0.02, and 0.002 annual probability of exceedance flood surfaces using default or user-defined flood elevation ratios and then

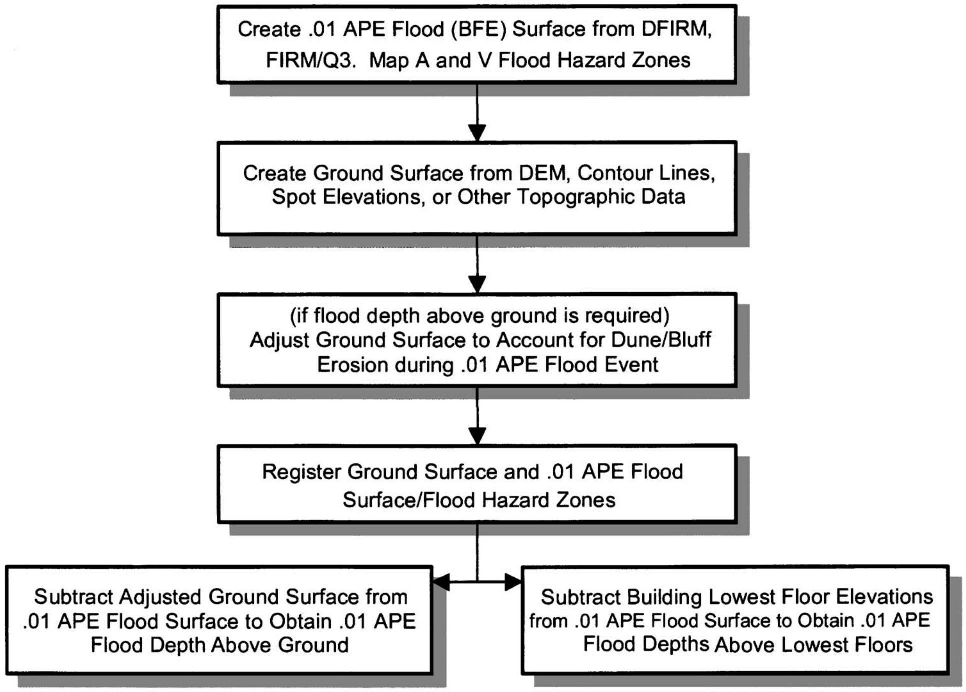

Fig. 9. Default (existing data) procedure for determining 0.01 annual probability of exceedance (APE) coastal flood hazard

interpolates other flood surfaces, if required. FIS reports are the best source of 0.01 annual probability of exceedance stillwater (swl) elevation data. The FIS supplies other useful information, including:

- If wave setup is included in the 0.01 annual probability of exceedance stillwater elevation (also termed the stillwater level, swl), the magnitude of the contribution must be removed from the 0.01 annual probability of exceedance swl before flood elevation ratios are calculated or applied; and
- Calculated 0.10, 0.02, and 0.002 annual probability of exceedance stillwater elevations, from which flood elevation ratios can be calculated (note that some FIS reports list only the calculated 0.10 and 0.01 annual probability of exceedance stillwater elevation—in those cases, default values can be used to calculate 0.02 and 0.002 annual probability of exceedance events).

Similar to riverine flood hazard, coastal flood hazard is also characterized by the flood depth above the ground, the magnitude of which at any location is determined by subtracting the ground surface from the flood surface. There are several important distinctions between the basic approach used to determine the coastal flood hazard and the basic approach used to determine the riverine flood hazard. These are

1. The general process required to generate the 0.01 annual probability of exceedance coastal flood surface is simpler than the process required to generate the 0.01 annual probability of exceedance riverine flood surface;
2. The coastal flood surface is not equivalent to the stillwater flood elevation. Instead it is defined by the wave crest elevation or the wave run-up elevation; and
3. The process by which the initial ground surface is generated for coastal areas is similar to that used to develop the ground surface in riverine areas. However, in coastal areas, a ground elevation higher than the flood elevation does not necessarily mean no flooding will occur. Flooding can occur at that location if the ground surface is lowered by dune or bluff erosion during a flood event. The initial ground surface must be adjusted for dune/bluff erosion before flood depths above ground can be calculated; however, if building floor elevations are known, the ground surface need not be adjusted. Flood depths above the lowest floor can be calculated and depth-damage functions can be applied to calculate building structure and contents damage.

The coastal flood surface for other return periods can be determined for many regions by multiplying the BFE by a simple ratio (n annual probability exceedance stillwater elevation/0.01 annual probability exceedance stillwater elevation). This procedure does not require complex or data-intensive hydrology and hydraulic calculations to determine flood elevations for other than 0.01 annual probability of exceedance flood events.

The default method for determining the coastal flood hazard is straightforward—the user needs to:

1. Map the 0.01 annual probability of exceedance flood elevation (BFE) surface and the ground surface;
2. Map the flood hazard zones as A zones or V zones (different depth-damage functions are applied in A and V zones);
3. Adjust the ground surface for dune/bluff erosion (see discussion below), if flood depths above ground are required; and
4. Subtract the adjusted ground surface from the BFE surface to determine the 100-year flood depth.

Dune Erosion

An important aspect of characterizing coastal flooding is incorporating the protection that dunes provide to the areas behind them and the damage the dunes themselves may sustain during coastal flooding events. In situations where the dune cross-sectional area above the 0.01 annual probability of exceedance stillwater level and seaward of the dune crest is less than 540 ft^2, the dune is considered to be fully eroded during the 0.01 annual probability of exceedance flood. The eroded ground profile at a transect is estimated by drawing an upward-sloping line, beginning at the intersection of the ground surface and the 0.10 annual probability

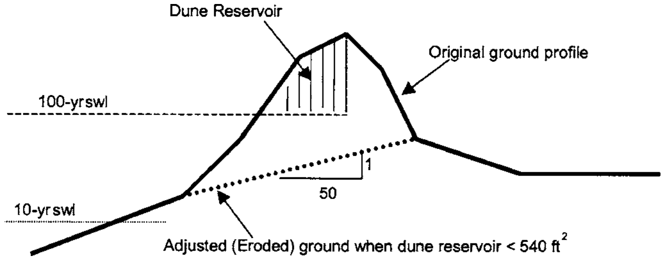

Fig. 10. Adjusted (eroded) ground profile along a transect

of exceedance stillwater elevation, and extending landward until it intersects the ground surface a second time. All soil above the sloping line is removed. Figs. 10 and 11 illustrate this. Fig. 10 provides a general depiction of the procedure, while Fig. 11 shows the application of the procedure to a transect at Pensacola Beach, Fla.

Wave Effects

Shorelines are divided into six basic types for use in the Flood Model (see Table 1). The classification is taken from *Guidelines and specifications for wave elevation determination and V zone mapping* (FEMA 1995), and is used by FEMA's mapping contractors. The shoreline types determine which of the three main flood-modeling procedures: (1) dune/bluff erosion assessment; (2) wave run up model; or (3) wave height model, are used in a particular situation. The FIT uses this shoreline classification to determine whether a dune/bluff erosion assessment should be run and the coastal Flood Model uses the classification to determine when each of the models listed in Table 1 should be run.

In the coastal Flood Model, wave exposure at the shoreline is divided into four categories (see Table 2). The FIT uses the wave exposure classification to determine whether a dune/bluff erosion assessment should be run and the coastal Flood Model then uses the classification to determine the incident wave conditions (i.e., wave height and wave period) at the shoreline. These are inputs to the wave run-up and wave height models. Model users are also able to input specific wave height and period data instead of accepting the regional default values, which may be desirable if the user has local wave information, or if another model provides local wave conditions. The HAZUS users' manual provides guidance on determining shoreline wave exposure and inputting specific wave condition data.

For the FIT or the coastal Flood Model to perform a dune/bluff erosion assessment, two conditions must exist:

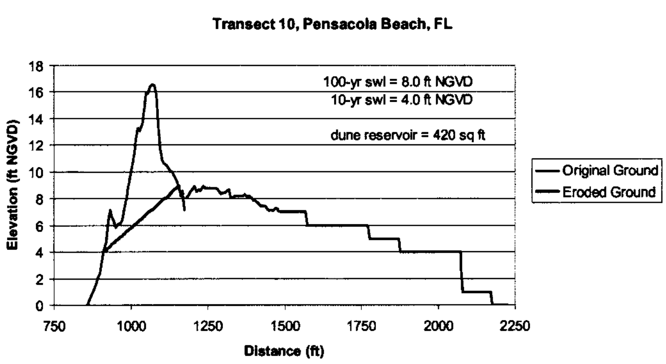

Fig. 11. Original and eroded ground, transect 10, Pensacola Beach, Fla.

1. The shoreline type must be classified as erodible (see Table 1, i.e., sandy bluff or dune type shoreline); and
2. Wave conditions at the shoreline must be capable of eroding the dune/bluff during the flood event.

For the coastal Flood Model to perform wave height and/or run up analyses, wave heights and periods must be above some threshold capable of producing damaging waves or wave run up. If shore protection structures exist (or are contemplated), the user must specify the level of protection afforded by the structure to areas behind the structure. Level of protection is taken to mean protection against erosion and protection against wave attack. The Flood Model technical manual provides detailed guidance on this topic.

Level Two Analyses Using FIT

The FIT is used for Level 2 analysis where site specific or higher resolution flood hazard data are available. The FIT preprocesses the user-supplied data to meet the format and file structure requirements of the Flood Model. While the FIT is a component of the Flood Model, the results may be used within the users' GIS for other applications where flood depth information is needed. A schematic of the FIT is provided in Fig. 4, which shows example input data types and the primary output. Key features of the FIT are that it:

- Accepts user-supplied data and is flexible enough to accept a variety of user-supplied terrain and flood hazard data;
- Contains algorithms that interpolate flood elevations between cross sections (riverine flooding) and across base flood elevation polygons (coastal flooding);
- Performs flood depth analysis by calculating grids of flood depths throughout the study area;
- Performs flood frequency analysis and provides depth grids for a variety of user-specified return periods;
- For coastal flooding only, the FIT performs analysis of flood-induced erosion using algorithms that model potential failure of the frontal dune in order to calculate a grid of flood-induced erosion depth. The FIT procedure is similar to the procedure used in FEMA coastal flooding studies; and
- Provides guidance via help functions to help users transform their flood hazard data into the formats required by the FIT.

FIT Riverine Analysis Procedures

The riverine analysis capability of the FIT was developed to allow users to incorporate results of their own, stream-specific, hydraulic modeling. The spatial data required to run the riverine portion of the FIT are a DEM, a set of polylines (cross sections) attributed with flood elevations, and a polygon that defines a representative floodplain boundary. The following is a description of the steps in a FIT analysis.

Step 1: Input Floodplain Boundary. Users are required to identify the up- and downstream limits of the study area and the shape file field(s) that contains the elevation data in a polyline shape file. These data are used in later steps by the FIT to define a "smooth" line representing the general flow path of floodwater.

Step 2: Determine the Centerline of Flow. Once the stream limits have been chosen, the program defines a polyline from the upstream limit to the downstream limit. The program uses the centerline to identify cross sections within the reach.

Table 1. Coastal Flood Hazard Modeling Process

Activity		Flood model	FIT
Shoreline characterization	1. Limit study area	U-R	U-R[a]
	2(a). Identify shoreline(s) for analysis	U-R	N/A
	2(b). Draw shoreline(s) for analysis	N/A	U-R
	3. Segment and characterize shoreline(s): 1%, 1% APE swl, wave setup, shoreline type, level of protection, wave exposure	U-R[b]	U-R
	4. Smooth shoreline for transect construction	P	P
	5. Draw transects	P[c]	P[c]
	6. Edit transects (spacing, location, orientation, length)	N/A	U-O
Eroded ground	7. Select dune/bluff peak and toe for erosion analysis	P	U-O[d]
	8. Calculate eroded ground elevations along transects	P	P
	9. Interpolate to determine eroded ground surface between transects	P	P
100-year flood hazard	10. Supply 1% APE flood surface polygons (flood zone and elevations)	N/A	U-R
	11. Select model type (WHAFIS, RUNUP) and version (Atlantic/Gulf, Great Lakes, Pacific) for analysis	P	N/A
	12. Calculate WHAFIS and/or RUNUP elevations along transect	P	N/A
	13. Test for flooding from adjacent transects	P	N/A
	14. Interpolate between transects to develop 100-year flood surface	P	N/A
	15. Repeat steps 2–14 for analysis of other flood sources	U, P	U, P
	16. Merge 1% APE flood surfaces to determine highest 100-year flood elevation and most hazardous zone at every grid cell	P	N/A
	17. Calculate 1% APE depth grid and vertical erosion grid	P	P
n-year flood hazard	18. Flood elevation ratios for other return period analyses	U-O[e]	U-O[e]
	19. Calculate 10, 2, and 0.2% APE flood surfaces; interpolate other return period flood surfaces	P	P
	20. Calculate other return period depth grids and vertical erosion grids	P	P
What-ifs	21. Long-term erosion	U-O	Flood model
	22. Shore protection	U-O	Flood model
	23. Beach nourishment	U-O	Flood model

Note: U=user action; R=required; O=optional; P=program completes activity; and N/A=activity not supported or undertaken.

[a]User "selects" study area by supplying terrain and flood surfaces over a common area.

[b]The only required user input for Level 1 is 1% APE swl—model assumes erodible ground and regional default wave conditions unless user overrides.

[c]Shore-perpendicular transects are used by Level 1 for eroded ground, flood hazard, and what-if calculations; transects are used by FIT for eroded ground and what-if calculations.

[d]Model selects a dune/bluff peak and toe; user can edit locations in FIT, but not in Level 1.

[e]Model has default values, editable by users in both Level 1 and FIT.

Table 2. Shoreline Wave Exposure Classification for Coastal Flood Model (Level 1 Users)

Wave exposure at shoreline	Typical location	Wave height at shoreline (ft)	Wave period at shoreline (s)
Exposed, open coast (maximum possible wave conditions—fully developed waves)	Shorelines directly fronting Atlantic, Gulf of Mexico, Pacific, Great Lakes (deepwater with fetches >10 mi)	$H_{max}=0.78$ times local stillwater depth	$T_{peak}=10-18$ s (varies by region)
Partially exposed (wave conditions somewhat reduced from maximum by fetch)	Large bays and water bodies, with fetches between 2 and 10 mi	$H \leqslant H_{max}$	$T < T_{peak}$
Partially sheltered (wave conditions significantly reduced from maximum)	Small bays and water bodies, with fetches between 1/2 and 2 mi	$H \ll H_{max}$	$T \ll T_{peak}$
Sheltered (no appreciable waves capable of causing erosion or building damage—essentially stillwater flood conditions)	Water bodies, with fetches <1/2 mi	$H \approx 0$	$T \approx 0$

Note: Wave heights and periods vary by region and by degree of exposure. Regional default values employed.

Step 3: Determine the Conveyance Bounding Polygon. An initial buffer is computed around the centerline and the user is prompted to increase and/or decrease the buffer until satisfied that the conveyance area of the floodplain of interest is contained within the buffer. The lengths of the cross section lines and the limits do not restrict the size of the bounding polygon. If necessary, the program extends cross-section lines to the bounding polygon in a manner that preserves a sense of alignment perpendicular to flood flow.

Step 4: Determine the Nonconveyance Areas. Certain low-lying areas adjacent to the floodplain, such as tributary streams, that do not convey but, rather, retain floodwater (pond) at the flood elevation in the conveyance part of the floodplain need not be included within the bounding polygon. The FIT provides an analysis option for including such areas inside and outside of the bounding polygon.

Step 5: Interpolation of Additional Hazard Grids. If the cross sections are attributed with multiple flood elevations, the FIT uses the information supplied for the initial analyses to develop flood depth grids for the other flood conditions.

FIT Coastal Analysis Procedures

The coastal portion of the FIT allows users to incorporate data from coastal flood hazard maps produced by FEMA, or others, including DEMs, polygons attributed with BFEs, FEMA flood hazard zones (e.g., zone VE, zone AE), and polygons representing the analysis boundaries. The following is a description of the steps in the FIT analysis for determining coastal flooding.

Step 1: Shoreline Characterization. The user is required to identify all possible coastal flooding sources and to draw a shoreline associated with each source. The user then divides each shoreline into segments of similar physical characteristics and wave exposure, such as rocky bluffs, sandy bluffs, little beach, sandy beach with small dunes, sandy beach with large dunes, open wetland, and erosion protection structures. The user must provide the 0.01 annual exceedance probability stillwater elevation at each shoreline segment, along with any contribution from wave setup. The FIT relies on the 0.01 annual exceedance probability stillwater elevation (without setup) to calculate 0.10, 0.02, and 0.002 annual exceedance probability stillwater elevations based on nationwide default data. Based on the shoreline segmentation, the FIT generates shore-perpendicular transects from each shoreline segment that are developed using a predetermined spacing, and then extend inland from the shoreline.

Step 2: Determine Frontal Dune Erosion. The FIT creates a profile (ground elevation versus distance inland from the shoreline) for each transect crossing an erodible shoreline segment with sufficient wave action to cause erosion of dunes and bluffs or failure of erosion protection devices during the base flood. The user may select the peak and toe of the dune/bluff, or accept the FIT selections. The FIT then calculates an eroded ground profile along each transect and interpolates an eroded ground elevation grid.

Step 3: Determine Output Hazard Grids. The FIT calculates the flood depth grid return periods selected by the user. This information is passed to the Flood Model, along with other information including shoreline characteristics, transect data, stillwater elevations, and flood hazard zone information for subsequent damage and loss analysis.

Conclusion

Flooding is a major hazard in the United States and addressing its often devastating effects has been a central focus of several federal agencies, including FEMA and the U.S. Army Corps of Engineers, as well as a major burden for thousands of state and local government officials for many decades. Effective flood management requires a coordinated, integrated approach that uses structural defenses at the edge of the floodplain as well as wise land use planning and restraints on construction within floodplains. Until now, quantitative assessment of the benefits of land use planning and building regulation have required detailed, resource-intensive analyses that can be prohibitive for many communities. The development of the HAZUS Flood Model puts a powerful tool in the hands of communities, allowing proactive analysis and mitigation at the local level. The HAZUS Flood Model is based on an integrated set of flood hazard analysis algorithms, using national elevation and other hydrologic and hydraulic datasets. An important aspect of the HAZUS Flood Model is the FIT, which permits rapid analysis of a wide variety of data with various GIS formats to determine flood-frequencies over entire floodplains. The cost of obtaining an estimate of potential flood losses using HAZUS is a function of the desired accuracy and confidence in the results, but a Level 1 analysis can be performed relatively quickly using default data supplied with the software (together with DEM data downloaded from the USGS website), at a nominal cost.

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