HAZUS-MH Flood Loss Estimation Methodology.
II. Damage and Loss Assessment

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Abstract: Part I of this two-part paper provided an overview of the HAZUS-MH Flood Model and a discussion of its capabilities for characterizing riverine and coastal flooding. Included was 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. This paper 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 effects of flood warning, the benefits of levees, structural elevation, and flood mapping restudies are also facilitated with the Flood Model.

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Introduction

This is the second part of a two-paper summary of the Flood Model of the HAZUS-MH software. Part I of this two-part paper provided an overview of the HAZUS Flood Model and a discussion of its capabilities for characterizing riverine and coastal flooding (Scawthorn et al. 2006). This paper reports on the damage and loss estimation capability of the Flood Model. For further detail, the reader is referred to EQE (1998, 1999a,b) and EQE International (1999a,b).

Inventory and Valuation

Most aspects of building and other inventory are common to all three models of HAZUS (earthquake, wind, and flood) and will not be discussed here. However, one aspect unique to the Flood Model has to do with depreciation. In loss estimation in the seismic and wind arenas, cost of repair is the general measure of economic loss, which effectively equates to new construction cost, and depreciated value as a factor in loss estimates for earthquake or wind is rarely considered in most seismic and wind analyses, and not at all in HAZUS. The flood arena differs significantly in this regard, due to the influence of the National Flood Insurance Program, which pays claims on the basis of depreciated value. Therefore, in the flood arena, it is important for some users to estimate losses on the basis of depreciated value. The HAZUS Flood Model therefore differs from the HAZUS Earthquake and Wind models in that it provides a capability to estimate losses on the basis of depreciated value. To develop this capability, data from a widely used source for building costs (*Means* 2000) was employed, in the form of three tabular depreciation models for residential structures, based on actual structure age and general condition (Good, Average, and Poor). These models are shown graphically in Fig. 1.

The underlying assumption in the proposed methodology is that for any community, some combination of the full replacement cost models (economy, average, custom, or luxury) and depreciation models (very good, good, average, or poor) best represent the true depreciated value. This basic premise was tested on more than 8,000 homes in Grand Forks, N.D., more than 160,000 homes in Mecklenburg County, N.C., and more than 60,000 homes in Fort Collins, Colo. Results indicated that good agreement with assessed (depreciated) value could be attained from the models.

Unlike the residential depreciation model, the Means commercial/industrial/institutional depreciation is determined from "observed age" and building framing material (frame, masonry on wood, and masonry on masonry or steel), although there is little variation between the models for the different framing types. Accordingly, an average depreciation model was developed and tested, and selected for implementation with the default inventory. A nonresidential structure's "observed age" is assumed to

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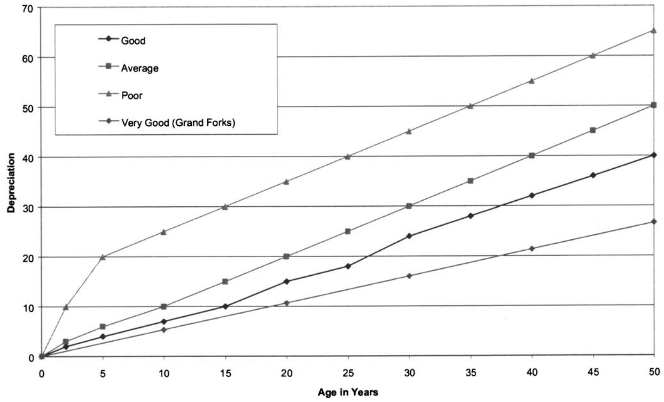

Fig. 1. Single family residential depreciation models (FEMA 2003, after Means 2002)

reflect the structure's condition (e.g., the observed age should reflect any remodeling or renovation that would reduce deterioration, and therefore decrease the observed age). The model is shown in Fig. 2.

During testing of the Flood Model, it was assumed that chronological age is approximately equivalent to observed age for the nonresidential structures, primarily because these structures are less likely to be used far beyond their typical life expectancy. (For example, in Grand Forks N.D. many homes are significantly older than the typical life expectancy of about 50–60 years, whereas commercial and industrial structures did not demonstrate the same widespread longevity.) Based on the results of the testing, it appears that the methodology produces reasonable approximations of current (depreciated) value employing this assumption. Accordingly, for the default inventory, age of nonresidential structures is assumed distributed in a manner similar to the residential structures in the same Census Block Group. It should be noted, however, that when the user inputs more detailed building inventory data at Level 2, entry of actual or "observed" age data for these structures is expected to supersede the default age data and to enhance their results. Default inventories are also provided in the HAZUS Flood Model for vehicles (i.e., cars and trucks), agricultural crops, population, and other aspects.

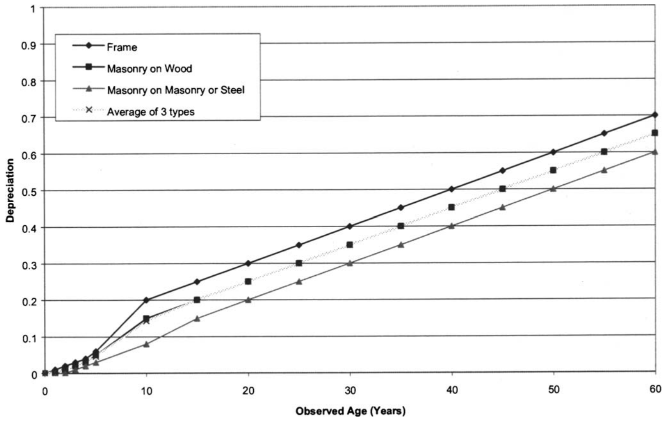

Fig. 2. Means commercial/industrial/institutional depreciation (FEMA 2003, after Means 2002)

Direct Damage

The HAZUS Flood Model uses estimates of flood depth along with depth-damage functions to compute the possible damage to buildings and infrastructure that may result from flooding. Two inputs to the damage module are required to estimate building damage: (1) the building occupancy type and first floor elevation, which typically include design levels (pre- or post-FIRM); and (2) the depth of flooding, at the building or area weighted throughout the census block where the building is located. The model building type may not be known for each building but it can be estimated from the default inventory using a relationship between the building type and occupancy. The depth of flooding is determined using the FIT for a Level 2 study or the Level 1 methodology contained in the Flood Model. The outputs of the damage module are area-weighted estimates of damage as a percent of replacement cost, at the census block or for a given building. These are used as inputs to the induced physical damage and direct economic and social loss modules.

Depth-Damage Functions

Depth-damage functions are plots of floodwater depth versus percent damage, plotted for a variety of building types and occupancies. The extent and severity of damage to structural components and contents are estimated from the depth of flooding and the application of the assigned depth-damage curve. While depth-damage functions are applicable to single buildings as well as groups of buildings of a given type, they are more reliable as predictors of damage for large, rather than small, groups of buildings.

The HAZUS Flood Model uses the Federal Insurance Administration's (FIA) "credibility weighted" depth-damage curves and selected curves developed by various districts of the U.S. Army Corps of Engineers (USACE) for estimating damage to the general building stock. For essential facilities, such as hospitals, schools, and fire stations, the damage is estimated by applying a default depth-damage curve, which is then editable by the user to create a specific function for the facility. Damage is estimated for lifeline systems with a separate set of damage functions that define the potential damage to components of the systems that are either uniquely vulnerable to inundation or are expensive to repair or replace. Various components are grouped based on similar vulnerabilities and expected loss.

Default curves to estimate structure and contents damage for Level 1 analyses were chosen for each HAZUS occupancy class for riverine and coastal flooding. More than 900 curves for structures, contents, and facilities are provided as discussed in the Flood Model technical manual. Excerpts are shown in Tables 1 and 2, and in Figs. 3 and 4. The default riverine damage functions for residential structures with basements have been modified from the original FIA functions, which reflect FIA policy exclusions, to now show total damage.

Table 3 lists the five model building types that are used in the Flood Model. For flooding, building damage is less a function of structural type than building materials and configuration, so that the HAZUS earthquake building types were simplified (versus the earthquake and wind model building types) in accordance with the different features important to flood damage. Unlike the Earthquake or Hurricane Models, where the building type, level of design, and quality of construction all play a critical role in the structure's ability to resist damage, these features do not play a major role in damage resistance to flooding. Structural failure

Table 1. Default Damage Functions for Estimation of Structure Damage (Partial)

HAZUS occupancy class	Flooding type/zone	Curve source	Curve description
RES1	Riverine/A-zone	FIA "credibility-weighted" depth-damage curves (CWDD)	1 floor, no basement 2 floor no basement 2 floor, split level, no basement
	Riverine/A-zone	Modified FIA CWDD	EQE-modified versions of FIA CWDD 2 floor, with basement 2 floor, split level, with basement
	Coastal/V-zone	FIA V-zone damage function	Combined curve (average of with and without obstruction)
	Coastal/A-zone	FIA V-zone damage function	Combined curve (average of with and without obstruction)
RES2	All zones	FIA CWDD	Mobile home
RES3	All zones	USACE–Galveston	Apartment
RES4	All zones	USACE–Galveston	Average of "hotel" and "motel unit"
RES5	All zones		No RES5 curves available—use RES6
RES6	All zones	USACE–Galveston	Nursing home
COM1	All zones	USACE–Galveston	Average of 47 retail classes
COM2	All zones	USACE–Galveston	Average of 22 wholesale/warehouse classes
COM3	All zones	USACE–Galveston	Average of 16 personal and repair services classes
COM4	All zones	USACE–Galveston	Average of "business" and "office"
COM5	All zones	USACE–Galveston	Bank
COM6	All zones	USACE–Galveston	Hospital
COM7	All zones	USACE–Galveston	Average of four medical office/clinic classes
COM8	All zones	USACE–Galveston	Average of 15 entertainment and recreation classes

during flooding is rare unless floodwaters move with extremely high velocity, or structures and foundations become separated, or the structure is impacted by flood-borne debris. Major structural components generally survive flooding and the major damage in flooding is to structural finishes, contents, and inventory.

Damage to General Building Stock

The algorithm for estimating direct physical damage to the general building stock is quite simple, and is computed for each occupancy class in a given census block, with default damage functions along with estimated water depths (either riverine or coastal) to determine the associated percent damage. For example, the RES1 default inventory occupancy class is used with the designated default damage function, i.e., a one-story residence with no basement. The estimated percent damage is then multiplied by the total replacement value or the depreciated replacement value of the occupancy class in question to produce estimates of total damage, or total depreciated damage.

Damage to Essential Facilities

Depth-damage curves are used in a similar fashion for essential facilities through the use of editable default damage functions. All essential facilities are handled as point facilities. These facilities are defined as those that provide service to the community and those that should be functional following a flood, such as hospitals, fire stations, and schools. The effects of flood proofing

Table 2. Default Damage Functions for Estimation of Contents Damage (Partial)

HAZUS occupancy class	Flooding type/zone	Curve source	Curve description
RES1	Riverine/A-zone and coastal/A-zone	FIA "credibility-weighted" depth-damage curves (CWDD)	Residential contents—first floor only (for 1 floor, no basement) Residential contents—first floor and above(for 2 floor no basement, and 2 floor, split level, no basement)
	Riverine/A-zone	Modified FIA CWDD	EQE-modified versions of FIA CWDD Residential contents—first floor and above (for 2 floor, with basement, and 2 floor, split level, with basement)
	Coastal/V-zone	FIA V-zone damage function	Combined curve (average of with and without obstruction)
RES2	All zones	FIA CWDD	Contents—residential—mobile home
RES3	All zones	USACE–Galveston	Apartment contents
RES4	All zones	USACE–Galveston	Average of "hotel-equipment" and "motel unit-inventory"
RES5	All zones		No RES5 curves available—use RES6
RES6	All zones	USACE–Galveston	Nursing home-equipment
COM1	All zones	USACE–Galveston	Average of 47 retail classes—equipment and inventory, when available

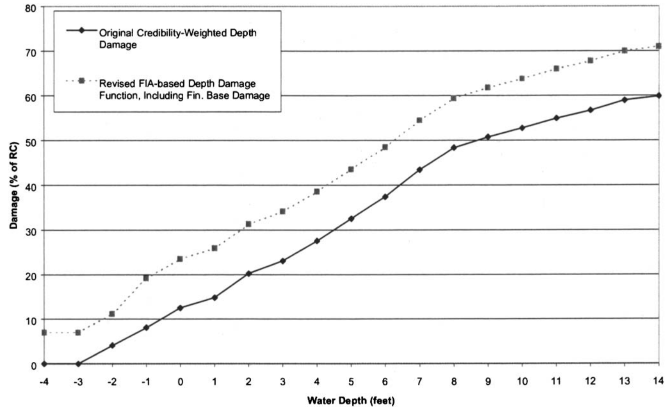

Fig. 3. FIA-based structure depth-damage curve, two or more stories, basement-modified

essential facilities can be accounted for by modifying the depth-damage functions to reflect the level of expected protection provided by flood proofing measures.

Damage to Lifeline Systems

Damage to transportation and utility lifeline systems is estimated based on the vulnerabilities of the various components to inundation, scour/erosion, and debris impact/hydraulic loading. The lifeline components selected for fragility modeling are bridges; water and wastewater system components with medium exposure; and electrical power, communications, natural gas, and petroleum lifeline systems that have vulnerabilities similar to water and wastewater systems. Impacts to system functionality, relative cost of component, and overall time to recover from damage are also taken into consideration.

Damage to Vehicles

Damage to vehicles from flooding can be substantial, particularly if limited warning is provided. The Level 1 user can estimate damage directly from the Flood Model and the Level 2 user can supply local information on vehicle fleets and locations. Damage functions were developed based on the location of critical vehicle components in passenger cars, light trucks and heavy trucks, and the depth of inundation, Fig. 5.

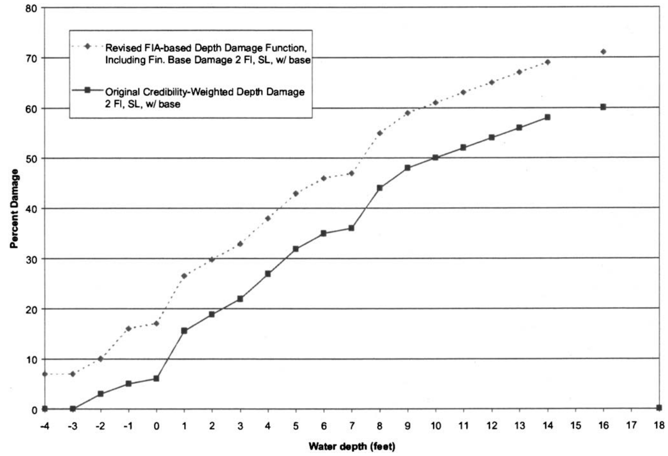

Fig. 4. FIA-based structure depth-damage curve split level, basement-modified

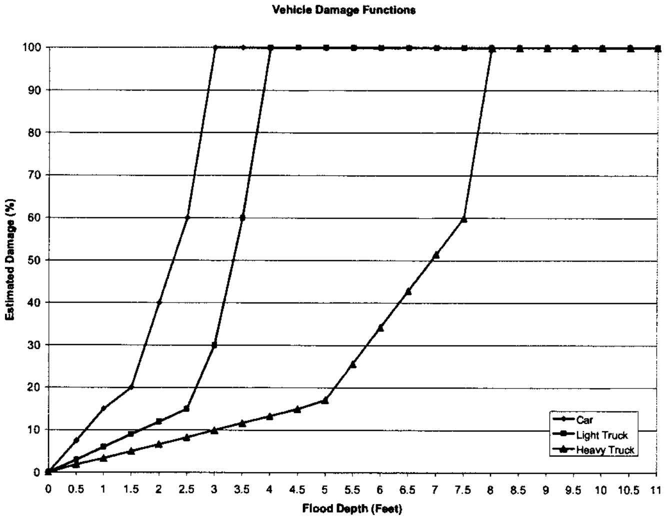

Fig. 5. Vehicle depth damage functions

Damage and Loss to Agriculture (Crops)

Damage to crops depends on the timing and duration of flooding and not on the depth of flooding. The Flood Model provides damage functions based on calendar date and duration modifiers based on Julian calendar dates (i.e., continuous count of days). The model automatically converts calendar date to Julian date. The user is able to modify the damage functions based on local planting cycles.

Losses are estimated based on the area of inundation versus total area of cropland and the subsequent reduction in output, investment, and income. The loss model is based on the Corps of Engineers AGDAM methodology and program. The users are required to provide a date of flooding (calendar) and the Flood Model estimates losses based on standard durations of 3, 7, and 13 days provided by the Corps of Engineers.

Consideration of Warning in Depth-Damage Relationship

Flood forecasting is a regular occurrence today and the capability for estimating possible reduction of flood damage by taking actions after warning is provided in the Flood Model by consideration of warning time and altering depth-damage functions. Background information detailing the implementation of damage reduction was reviewed to identify applications within the Flood Model for damage reduction based on flood warning (USACE 1984; URS 1992a,b; USACE 1994).

The effectiveness of flood warning in reducing damage is estimated by modification of Day curves, developed by Harold Day in a series of publications in the late 1960s, and damage reduction related to forecast lead time, which is defined as the time required for warning dissemination and effective public response. The Day method introduced the consideration of warning time to the depth-damage relationship. An example of the use of a Day curve for riverine flooding in a residential area is presented in Fig. 6. The original Day curve indicates a maximum loss reduction of 35% of total damage (e.g., structure and contents), and assumes a

Table 3. Flood Model Building Types

			Height			
			Range		Typical	
Number	Label	Description	Name	Stories	Stories	Feet
1	Wood	Wood (light frame and commercial and industrial)		All	1 to 2	14–24
2	Steel	Steel frame structures including those with infill walls or concrete shear walls	Low-rise	1–3	2	24
			Mid-rise	4–7	5	60
			High-rise	8+	13	156
3	Concrete	Concrete frame or shear walls including tilt-up, precast, and infill walls	Low-rise	1–3	2	20
			Mid-rise	4–7	5	50
			High-rise	8+	12	120
4	Masonry	All structures with masonry bearing walls	Low-rise	1–3	2	20
			Mid-rise	4–7	5	50
			High-rise	8+	12	120
5	MH	Mobile homes		All	1	10

public response rate of 100%. A response rate of 100% is not likely in all circumstances, and as such the New York District of the USACE modified this and some of the other major lead time assumptions inherent in the Day curve as follows:

1. Building location. Forecast lead-time will vary at each building, based on water velocity, storm type (riverine or flash flood), basin time of concentration, and structure elevation. These variables were considered to develop a mean forecast lead-time for the Passaic River basin, defined as the average time available for public response;
2. Warning dissemination. The speed of warning dissemination is affected by several factors, including the dissemination medium (TV, radio, siren, etc.), time of day, source, and content. As such, the public will receive the flood warning at varying times. The New York District used this understanding to develop distributions of warning dissemination; and
3. Public response. Once the warning is disseminated, all residents will not respond with damage reduction activity at the same rate. Research has shown that the public response rate is conditioned upon demographic factors, such as age, income, ethnicity, and past experience with floods. The District used the results of a literature review to develop a public response time distribution, which was capped at a rate of 85%.

Users are allowed to make a few simple modifications, as follows:

1. The user must enter warning time in hours (default is no warning, and accordingly, no damage reduction);
2. The default assumption for the maximum reduction in damage to contents is set at 35%, varying as shown on the Day Curve. The user has the option to adjust the maximum damage reduction, and the software automatically scales the damage reduction function accordingly;
3. The user is asked to enter the percent of the population that heard the warning, and the function is scaled down accordingly (default=100%);
4. The user is asked to enter the percent of the population that responded to the warning, and the function is scaled down accordingly (default=100%); and
5. The user may opt to apply the damage reduction factor to structure damage (in addition to contents damage) if flood-fighting efforts (e.g., sandbagging, etc.) are considered significant.

Debris Generation

Flooding results in significant amounts of debris that is comprised of building contents, such as furniture, and finishes, such as carpeting, flooring, and drywall, rather than the debris resulting from collapsed structural components that result from earthquakes. The flood debris model reflects this and consists of two components:

1. For buildings with less than 50% damage, the debris model is based on flood depth and occupancy type. In each depth range (0–4 ft, 4–8 ft, etc.), a simplified engineering-based component analysis was performed to identify building components requiring replacement (i.e., wood subfloor, carpet, and wall finishes) and to estimate their weight.
2. For buildings exceeding the 50% damage threshold, the building is assumed to be a total loss, and will be demolished with no salvage. In that case, the total debris weight will include structural components such as wood, concrete, and steel. The method used to estimate structural debris is adapted from the HAZUS Earthquake debris model.

Direct Economic Losses

Within the Flood Model methodology, direct economic losses include building repair and replacement costs (structural and non-structural damage), building contents losses, building inventory

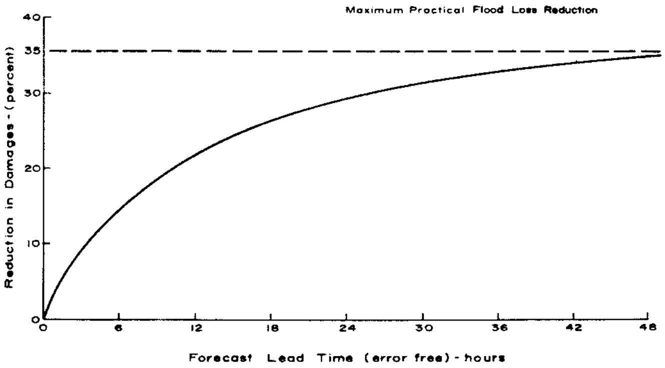

Fig. 6. Day curve for residential areas (source: USACE, New York District, 1984)

losses, relocation expenses, capital related income losses (previously loss of proprietor's income), wage losses, and rental income losses. The first three categories are building-related losses termed Capital Stock Losses, while the last four are time-dependent income losses, requiring an estimation of building restoration or outage time.

Direct economic losses for the Flood Model are similar to those in the Earthquake Model, except that where earthquake losses depend on damage state probability, flood losses depend on depth-related percent damage. Additionally, the Earthquake Model estimates damage and losses to structural and nonstructural components separately, while the Flood Model estimates one aggregate "building" loss. In addition to the existing income losses, the Flood Model incorporates output losses and employment losses (in terms of the number of jobs).

Other Direct Losses

Income losses depend on the length of time needed to restore business operations and include the time for physical restoration of the buildings and time for clean up, inspections, permits, and delays due to contractor availability. A flood-specific restoration time model was developed, based on the Earthquake Model methodology, that provides estimates of time required based on occupancy and flood depths, which are given in 4 ft increments to coincide with likely physical repair strategies. Restoration time increases with flood depth until the building has reached the 50% damage threshold, beyond which the building is considered a total loss. At the point of 50% damage, it is assumed the building will be demolished and rebuilt.

Social Losses and Induced Damage

Shelter Needs

An important task for any natural hazards planning scenario is to estimate the number of individuals who will need short-term shelter. Modifications have been made to the algorithm developed for the Earthquake Model to reflect the difference in sheltering needs between earthquakes and flooding events, so that flood sheltering needs are based on the numbers of displaced people and not on the degree of damage to structures. The Flood Model determines the number of individuals likely to use government-provided, short-term shelters by estimating the number of displaced households in inundated areas and the corresponding number of individuals, modified by factors accounting for income and age. Those displaced persons using shelters will most likely be individuals with lower incomes and those who do not have family and friends within the immediate area. Age plays a secondary role in that there are some individuals who will seek shelter even though they have the financial means of finding their own shelter and will usually be younger, less established families and elderly families. Displaced individuals and households are also made up of those whose buildings have not been damaged but who were evacuated when a warning was issued, or there is no physical access to the property because of flooded roadways.

Indirect Economic Losses

This section provides an overview of the Indirect Economic Loss Methodology (IELM) that was developed to evaluate indirect economic impacts in the Flood Model. Disasters such as earthquakes or floods may produce dislocations in economic sectors not sustaining direct damage. All businesses are either forward-linked (i.e., rely on regional customers to purchase their output) or backward-linked (rely on regional suppliers to provide their inputs) and are thus potentially vulnerable to interruptions in their operations, even if not directly damaged. These interruptions are termed indirect economic losses. Note that these losses are not confined to immediate customers or suppliers of damaged enterprises. All of the successive rounds of customers and suppliers are impacted. In this way, even limited physical damage causes a chain reaction, or ripple effect, that is transmitted throughout the regional economy. The extent of indirect losses depends on factors such as the availability of alternative sources of supply and markets for products, the length of the production disturbance, and deferability of production. Because no standard methodology for estimation of indirect economic losses resulting from floods exists, the Flood IELM builds on the IELM in the Earthquake Model. It is envisioned that ultimately, HAZUS will employ a single IELM usable for multiple hazards, including flood, earthquake, and wind.

As in the Earthquake Model, Level 1 analysis in the Flood IELM requires minimal user inputs. The user selects the synthetic economic type that best represents the study area. In Level 2 analysis, the user provides economic data from impact analysis for planning [(IMPLAN), a well-known economic modeling system, discussed further in ABS (2002)] for the study region. Efforts for the development of the Flood IELM focused on (1) addressing differences between flood and earthquake impacts on regional economies, and (2) providing better support for the intended uses of the model. In adapting the Earthquake IELM to flooding, it was recognized that the types of economies at risk from floods typically differ from those exposed to earthquake. Specifically, the methodology was enhanced to encompass agriculture- and tourism-based economies. A second difference between floods and earthquakes is that the area directly impacted by a flood is typically smaller, both absolutely and relative to the urban area (generally confined to the floodplain). This suggests that while bottleneck effects or supply constraints may dominate in earthquakes, floods may be better characterized as causing demand-driven impacts, producing dislocations that could be readily modeled using simple multiplier analysis. This can be readily handled within the existing IELM model structure.

The Flood IELM adds a new capability to evaluate economic impacts related to agricultural losses. For Level 1, a new series of synthetic economic tables is provided that represents agriculture-based economies of various sizes. After investigating various sectoral disaggregation schemes, it was decided that the agriculture synthetic economies should follow the same 10-industry structure as the other synthetic economies (e.g., service- or manufacturing-based). However, in contrast to these other economies, three size classifications rather than four are provided. Moreover, the size classifications are based on regional agricultural dependence rather than employment ranges. In Level 2, the user has to supply the IMPLAN economic tables specific to the study area. The direct loss "trigger" follows the same format for agricultural damage as for building-related damage. Estimates of crop loss from the Agricultural Damage Module are converted to percent output loss for the agriculture industry in the study area and input to the IELM.

The Flood IELM also adds a capability to evaluate economic impacts related to loss of tourism activity. After investigating various sectoral disaggregation schemes, it was decided to retain the existing 10-industry classification scheme and to treat tourism as a component of the service industry. There was little difference in multiplier values between the service sector aggregate and its tourist sector components. For a tourism-dominated economy, the user must select the "service-based" economic type in Level 1. This approach has the important advantage of allowing tourism-related impacts to be evaluated for any economic type, even one that is not actually dominated by tourism activities.

The methodology developed for tourism impacts differs from that for losses deriving from physical damage. Loss of visitors to the flood-stricken region is treated as a demand shock. Note that at the same time, the service sector may be subject to a supply constraint related to building damage to hotels, restaurants, etc. The IELM algorithm is able to handle both supply and demand losses simultaneously without double counting (for example, the Earthquake IELM treats damage-related constraints as supply shocks and reduced consumption due to loan repayment as demand loss). In Level 1, to evaluate the tourism demand loss, the user must provide estimates of the number of visitor-days lost and the time frame over which activity returns to normal. Default data are provided to translate this into the dollar and percent direct demand loss that is suffered by the service sector. The percent direct loss is then input to the IELM along with direct loss from other sources. For a Level 2 analysis, the user is allowed the option of entering either the number of visitor days lost, the aggregate of expenditures lost, or a vector of such expenditures. In both levels, the module makes the necessary trade margin and import adjustments. The user can, of course, elect not to evaluate tourism-related losses.

If tourism impacts are evaluated, the model automatically constrains certain parameters for the services sector. The IELM algorithm works by seeking opportunities to get rid of excess supply (e.g., through exports) or meet excess demand (e.g., through imports) as it seeks to rebalance supplies and demands throughout the economy. To ensure that the model does not import or export hotel services to/from the region, for example, import and export parameters for the services sector need to be set to zero. Allowance for excess capacity, such as normal hotel vacancy rates, could be built in through the "inventory" parameter of the model.

The Flood IELM also adds a capability to evaluate tax revenue losses to the government sector. In Level 1, the methodology evaluates an aggregate tax revenue impact by multiplying the change in sectoral outputs by indirect business tax (IBT) coefficients. IBT coefficients are provided by IMPLAN and have been developed for the synthetic economies. IBT includes property tax, sales tax, and licenses and fees. These components accrue variously to local, state, and federal governments. Because IMPLAN does not disaggregate IBT into its components, Level 1 results pertain to aggregate IBT.

Level 2 provides a more refined treatment of tax revenue loss, emphasizing impacts on local government. Here, the user supplies information on the local property tax rate and local sales tax rate, if any (i.e., excluding any state sales tax), and the categories of sales that are taxed. Since few jurisdictions impose local income tax, this category is not evaluated. Loss of property tax, a major source of local government revenue, is calculated from HAZUS direct damage estimates to buildings. The value of structural damage, excluding tax-exempt categories of buildings, is multiplied by the local property tax rate. As for local sales tax, this loss is evaluated by first identifying the subsectors whose sales are taxable (e.g., hotels) and their shares of the major sectors (e.g., services). IELM results on sectoral loss of output are then multiplied by taxable subsector shares to derive an implicit output loss to these subsectors. This is in turn multiplied by the tax rate to derive the loss of local sales tax revenue. The loss of local property and sales tax revenues, in addition to simply being reported, has an impact in the model on local government sector spending. Government consumption in each year is reduced by the amount of tax revenue loss in the previous year. While the current IELM evaluates impacts on regional income, the methodology has been further extended to assess the distributional impacts on various income groups. This provides some information on "winners" and "losers" in the disaster. The approach involves expanding the input-output (I-O) database that is currently used by the IELM to include data on a multisector income distribution matrix. This matrix contains the percentage of income that flows to each of nine income brackets from each of the 10 HAZUS I-O table sectors.

To estimate distributional impacts, output changes are first evaluated using the IELM rebalancing algorithm. The output changes are then premultiplied by the income distribution matrix to yield changes in income to each of the household income groups. In addition to these methodological refinements, output tables of the direct and indirect economic loss modules have been reformatted. The previous reporting format (HAZUS99 Earthquake Model) had some important deficiencies that impeded communicating IELM results to the user. HAZUS99 did not summarize total (direct plus indirect) economic impact in any of the output tables. For employment, it reported indirect but not direct impacts, thus rendering the information on indirect effects alone of limited value. Moreover, while production or sales impacts were apparently calculated by HAZUS99, they were not reported anywhere. To enhance user friendliness, two modifications were made in HAZUS: (1) the Quick Assessment Report includes indirect income impacts for Year 1, in addition to direct income impacts; and (2) a new summary report is provided for "Total Economic Impact."

Finally, an issue arose pertaining to the possibility of users specifying small study areas in the Flood Model. The Earthquake IELM was developed on the assumption that the study area for analysis would consist of a single county or possibly multiple counties. As a study area is decreased in size, it becomes more "open" and an increasing share of interindustry transactions are conducted with entities outside the region. Thus indirect effects are much less significant for small regions than for large ones. For flood analysis, a user could define a study region consisting of, say, a single river reach that made up a small fraction of a county. The evaluation of indirect economic impacts for such a small study area could very well be meaningless. The approach developed in HAZUS was to continue to model indirect impacts at the county level, which requires simply evaluating damage ratios for the entire county, even if damage itself is only estimated for a portion of the county. This required some software changes to the HAZUS shell to ensure that the county inventory data are available for use in the IELM. Adequate warnings are provided to users who try to run the IELM for very small study areas.

The various model refinements developed in HAZUS, and detailed in the technical manual (ABS Consulting 2002), result in an IELM that is appropriate for flood disasters. Moreover, the additional capabilities for looking at tax and distributional impacts, as well as the revised output formats, substantially improve the user-friendliness of the HAZUS IELM.

Additional Capabilities

In addition to the comprehensive loss estimation capability outlined above, several specific types of analyses commonly needed by users were identified.

Levees

A tool is provided in the Flood Model to allow users to add a levee to a study area, specify a level of protection for the levee, and, for Level 1 analyses, determine the effects of a levee on flood depths within the unprotected portion of the floodplain. This is needed since, in general, digital elevation models (DEMs) are not reliable for identifying relatively small physical features such as the narrow, continuous embankments that form levees.

Because grid cells are connected at the corners as well as the sides, an embankment that is not a straight line, in the strictest sense, must be at least two cells wide to be treated as a barrier to flow. In areas identified as protected by a levee, flood depths are zero for frequencies up to the recurrence interval of the level of protection provided by the levee. For recurrence intervals exceeding the level of protection, flood depths are those computed without consideration of the levee. Similarly, if the option to determine the effects of a levee is chosen, two sets of flood depth grids are created: one with the levee and one without the levee reflected in the DEM.

The levee option is applied by drawing a polyline with the mouse. Flood depth grids have been created for the reach and the user chooses a grid on which to draw the levee alignment. The alignment should cross the floodplain twice. The user is prompted to supply the recurrence interval, in years, corresponding to the level of protection provided by the levee.

If a flood depth grid has been created corresponding to the level of protection; or if enough grids have been created to interpolate that particular grid, the floodplain associated with that grid is determined. The levee alignment and section of that floodplain between the points where the alignment crosses the floodplain are used to define a polygon. If the floodplain associated with the recurrence interval cannot be determined, the floodplain associated with the flood depth grid chosen to draw the alignment is used to define the polygon. If the levee alignment does not cross the floodplain twice the user is notified and cautioned that the floodplain information and supplied levee alignment indicate that the levee does not provide the entered level of protection.

If flood depth grids were developed with Level 1 analyses, the user may choose to recreate the depth grids with the levee represented in the DEM. Note that because the default hydraulic analyses are performed using normal depth calculations (i.e., no consideration of backwater effects), flood elevations and, consequently, flood depths and the extent of floodplains will change only at cross sections within the levied portion of the reach. The effects of the levee on upstream cross sections will not be reflected.

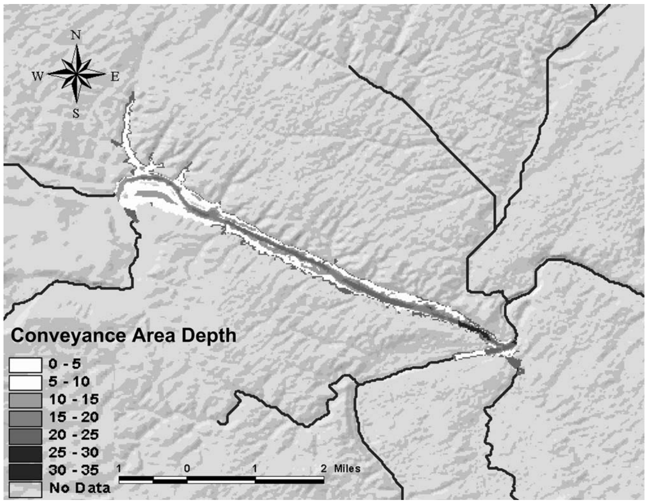

Fig. 7. Flood depths in nonconveyance areas

If the user chooses to investigate the local increases in flood depths resulting from a levee alignment, a buffer is created one cell size around the user-supplied polyline. The resulting polygon is attributed with a high elevation value and a grid is created from the polygon. Note that the grid, or levee, is everywhere at least two cells wide. That grid is merged with the DEM creating a new DEM that reflects a continuous levee. The protected area is then treated as a "pool" and, consequently, not included in the water surface elevation computations. Fig. 7 shows a (buffered) levee alignment supplied by a user and upstream portion of the "without" levee flood depth grid shown in Fig. 8. Fig. 9 shows the effects of the levee on the flood depth grid. Note, for example, the increase in the nonconveyance areas across the stream from the levee.

Flow Regulation

The default hydrologic analyses of a Level 1 analysis with the Flood Model apply to unregulated drainage areas. However, regulation, through diversions and/or storage, changes the flood frequency curves downstream. The Flood Model provides a tool for incorporating the downstream effects of flow regulation by allowing users to modify the unregulated flood frequency curve at a specific location by entering one or more pairs of recurrence intervals and discharge values. The Flood Model then identifies affected downstream reaches and modifies the corresponding flood frequency curves, as needed.

The process begins with users identifying the location of a regulating structure, such as a flood control reservoir. The algorithm finds the drainage area upstream of that location and defines

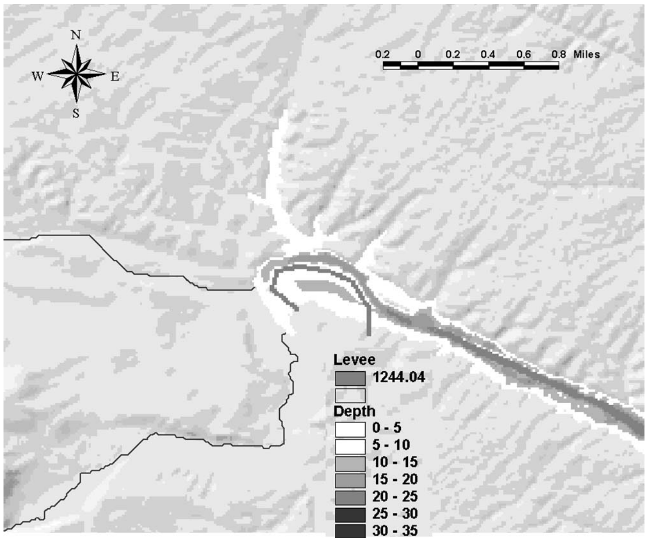

Fig. 8. User-supplied levee alignment

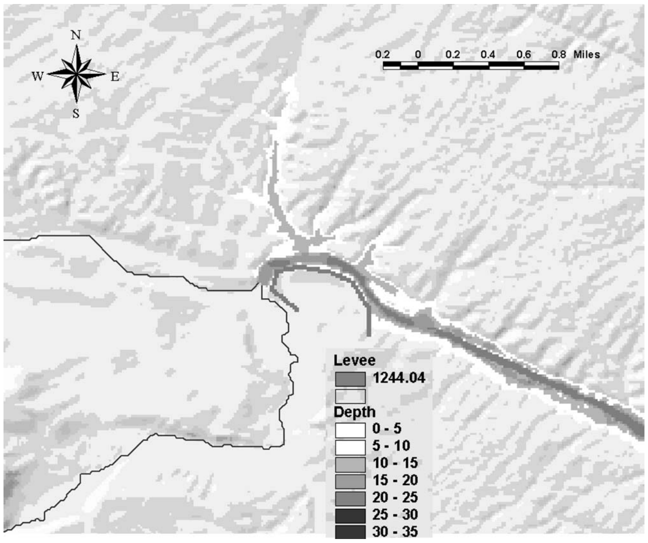

Fig. 9. Effects of levee on flood depths

the unregulated flood frequency curve. The curve is plotted and a table of recurrence intervals and associated discharge values is presented for the user to peruse and modify. As the user enters and/or modifies values in the table, both the curve and the table are revised to reflect the changes. The first modification results in revising all discharge values associated with recurrence intervals (frequencies) less (greater) than the user supplied recurrence interval to be no greater than the modified discharge value. Graphically, the curve is revised by drawing a horizontal line from the modified point to the point where that line intersects the unregulated curve. The curve is not revised for recurrence intervals greater than the recurrence interval of the user supplied point. Graphically, a vertical line is drawn from the modified point to the point where that line intersects the unregulated curve.

Fig. 10 shows the unregulated flood frequency curve associated with the most downstream reach of the North Fork of the Shenandoah River. The drainage area there is approximately 1,320 sq. mi. If the ramifications of placing a dam within the reach and controlling the outflow at 14,000 cubic feet per second (cfs) are studied, the dam would be large enough to control up to a 0.02 annual probability of exceedance flood. The regulated flood frequency curve at the outflow point is shown on Fig. 10. The revised part is shown as the dashed line. The modification was accomplished by entering a 0.02 annual probability of exceedance discharge value of 14,000 cfs, shown as the triangle on the curve. Subsequent modifications are incorporated by assuming a lognormal distribution (straight line on the graph) between points. Again, the point associated with the smallest modified recurrence interval is connected to the unregulated flood frequency curve with a line of constant discharge value (horizontal line). The point associated with the greatest modified recurrence interval is connected to the unregulated curve with a line of constant frequency (vertical line). The algorithm translates the effects downstream by assuming that the contribution to the unregulated flow at some point coming from any portion of the drainage area is proportional to the size of that portion. That is, a 132 sq mi area contributes 10% of the flow to our example reach. For a given recurrence interval, the reduction in flow at some point resulting from upstream regulation is determined as follows:

- The unregulated flow value is determined at the point;
- That value is multiplied by the ratio of the drainage areas of the regulated site and the point. The product is the unregulated contribution from the regulated site;
- The frequency associated with that unregulated contribution is determined;

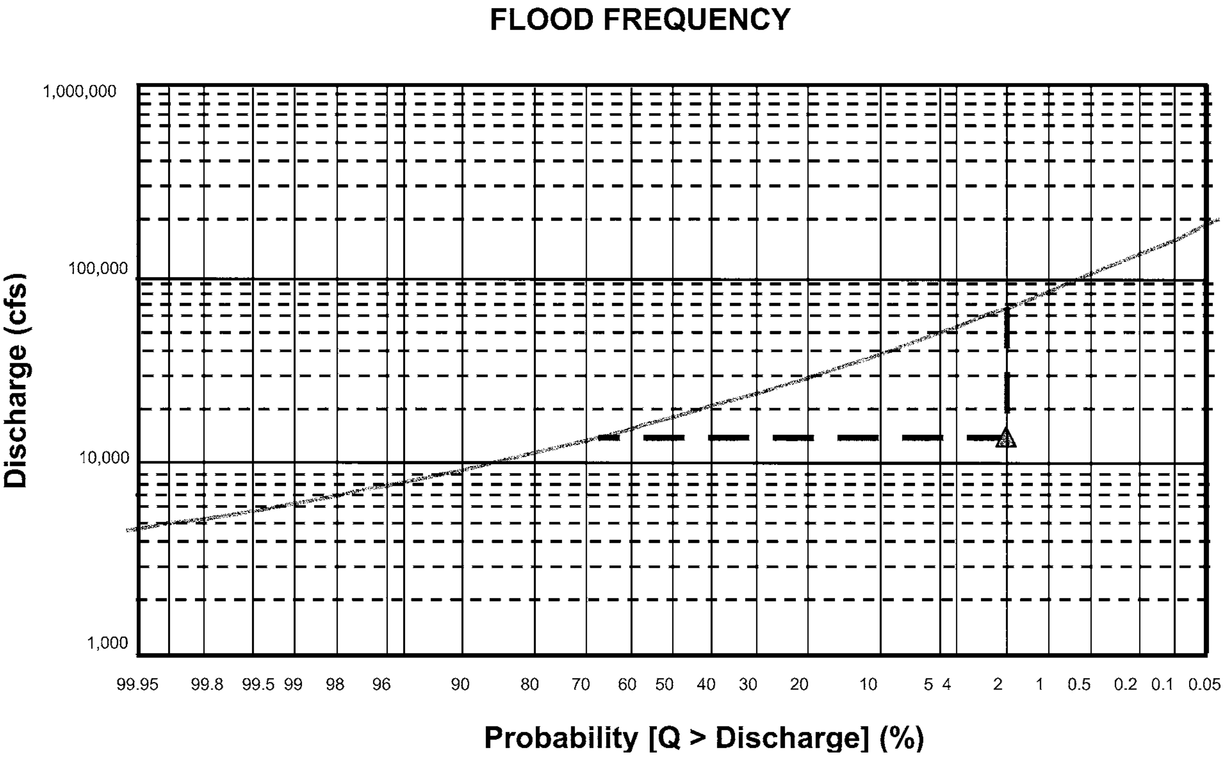

Fig. 10. Flood frequency curve

- The regulated flow value associated with that frequency is determined and subtracted from the unregulated value; and
- That difference is the reduction in flow at the point resulting from the upstream regulation.

The South Fork of the Shenandoah River joins the North Fork to form the Shenandoah River at the downstream node of our example reach. The drainage area there is approximately 3,000 sq mi. The 0.01 annual probability of exceedance flood discharge is approximately 142,750 cfs. In the algorithm, the contribution from the North Fork is 62,810 cfs, a little less than the 0.02 annual probability of exceedance flood discharge value. The regulated flow at the potential dam site is 14,000 cfs and therefore the reduction is 48,810 cfs. The effects of the dam downstream at the upstream node of the Shenandoah River would be to reduce the 0.01 annual probability of exceedance flood discharge value from 142,750 to about 93,940 cfs.

Such an analysis, including the accompanying loss estimation in HAZUS, can be used to justify a more detailed investigation into regulating the flow upstream.

Policy Analyses

Examples of cases involving policy decisions are provided in the Flood Model technical manual and a step-by-step discussion along with screen images guides the user through the process.

- Floodplain regulation—BFE+1 ft. This example demonstrates how the user can determine the impacts of the creation of modification of the floodplain regulatory requirements. The example analyzes the impact of requiring that every house within the floodplain be either built or retrofitted to BFE +1 ft. The example includes a Level 1 analysis using the baseline general building stock data and a Level 2 analysis using site-specific user-defined building inventory data.
- Flood mapping restudies. This example demonstrates the use of HAZUS to analyze losses through the use of updated floodplain boundaries that result from floodplain mapping restudies. The purpose is to demonstrate the value of remapping in land use planning and the resultant reduction in flood losses. The use of HAZUS to analyze potential losses under current and future land use scenarios is a valuable tool for policy makers.
- Building acquisition and removal. In this example the effects of the acquisition and removal of a single structure or a small number of structures on flood losses is analyzed. The example demonstrates how the user prepares the flood hazard data within the FIT, utilizes the InCAST (Inventory and Collection Tool) to prepare the inventory data, and imports the data into HAZUS. The example also demonstrates estimating annualized losses in the study area with and without the targeted structures.
- Flood forecasting. The current methodology allows the user to modify the damage functions for a given occupancy or even assign a unique damage function to a given census block. In this example screen captures of the model's dialog are provided to assist the user in accounting for flood forecasting. Since this effort involves modification to the damage functions, the example is applicable to Level 1 and Level 2 users alike.

Conclusion

Flooding is a major hazard in the United States, accounting for the single largest total property losses, and major life loss, of any single hazard. Flooding has a long history in the United States, and its mitigation has been a central focus of several federal agencies (FEMA, USACE, and others) for many decades, as well as a major burden for thousands of state and local government officials. Effective mitigation of floods involves a coordinated integrated approach, not only utilizing structural defenses at the edge of the floodplain, but also wise land use planning and restraints on building in the way of the water. Until now, any quantitative understanding of the benefits of land use planning and building regulation decisions required detailed resource-intensive analyses, which was prohibitive for many communities. The development of the HAZUS Flood Model puts a powerful tool in the hands of those communities, allowing proactive analysis and mitigation at the local level.

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