Assessing Flood Hazard Zones in the Absence of Digital Floodplain Maps: Comparison of Alternative Approaches

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Abstract: This article examines options for assessing flood hazards whenever digital floodplain maps are not available. Two floodplain-modeling approaches are assessed: USGS's stream flow model (SFM 3.3) and FEMA's natural hazard loss estimation software (HAZUS-MH). Both approaches are evaluated by spatially comparing their modeled outputs to existing Q3 flood data and when available, digital flood insurance rate maps (DFIRMs). The study area comprises three counties in South Carolina. The accuracy of the modeled flood zones was assessed through the use of error matrices, Kappa analysis, and the percentage of overlap between modeled floodplain and the Q3 floodplain. The results showed that HAZUS-MH (based on the first level of analysis) and SFM 3.3 are suitable workarounds whenever digital flood data are missing. However, these results are based on a limited sample of three sites and should be viewed as a pilot study. Nevertheless, the lack of consistently comparable results to Q3 data from both models underscores the urgent need for FEMA's map modernization program, especially in those areas where digital floodplain maps are not currently available.

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Introduction

The Disaster Mitigation Act of 2000 (DMA 2000) tied a community's eligibility for disaster assistance to the existence of federally approved mitigation plans. State and local governments can receive full federal disaster assistance only if they have identified natural hazards, risks, and vulnerabilities in their jurisdiction, and submitted comprehensive multihazard mitigation plans (U.S. Congress 2000). Yet, for many communities, flood mapping data are not available, so how can they achieve some semblance of a spatial assessment of flood hazard risk, thus averting financial penalties under the Disaster Mitigation Act?

This article presents simplistic methods for delineating flood zones for mitigation planning whenever detailed hydrologic and hydraulic (H and H) data, Q3 flood data, or DFIRMs are unavailable. Two floodplain-modeling solutions are compared USGS's stream flow model (SFM 3.3) and FEMA's natural hazard loss estimation software (HAZUS-MH), for their applicability and ease of use in hazards assessments and mitigation planning conducted by local officials. The approaches are evaluated by spatially comparing the model outputs (SFM 3.3 and HAZUS-MH) to Q3 flood data.

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The writers are fully aware of the limitations of Q3 data, but we reference the research findings to this dataset since it remains the planning standard under the Disaster Mitigation Act of 2000. It is also acknowledged that the methods presented here cannot substitute for a comprehensive engineering study on flood risks but can only serve as crude initial assessments.

Background

The Disaster Mitigation Act assigned responsibilities for technical assistance and support of local mitigation plans to each state, but for some, the mitigation planning process strains the capabilities and capacities of the states and local communities. Current "How-to Guides" published by FEMA have been adopted as the ad hoc blueprint for local communities in drafting their plans. For the identification of flood hazards, these guides recommend that local communities first obtain a copy of flood insurance rate maps (FIRMs) from the FEMA Map Service Center, verify if they are up-to-date, and modify them when necessary, but do not provide guidance on how to do the modifications (FEMA 2001).

FEMA conducts flood insurance studies and creates FIRMs only in those counties who participate in the National Flood Insurance Program. The locations of flood hazard zones on the hard copy (paper) maps are derived from hydraulic and hydrologic (H and H) engineering models. At the present time, nearly 70% of all FIRMs are outdated and unreliable since they were published more than ten years ago (General Accounting Office 2004). They are also difficult to use because they are paper maps and many lack a spatial reference system (Jones et al. 1998), yet they remain the legal standard for determination of whether individual parcels of land are inside or outside the floodplain. Digital alternatives to FIRMs are the Q3 flood data, which are simply scanned versions of the original hard copy FIRM documents with selective digitizing of features and lines. Q3 flood data are scaled to the USGS 1:24,000 topographic maps and are intentionally designed for use as planning guidance at the community or county level, not as a

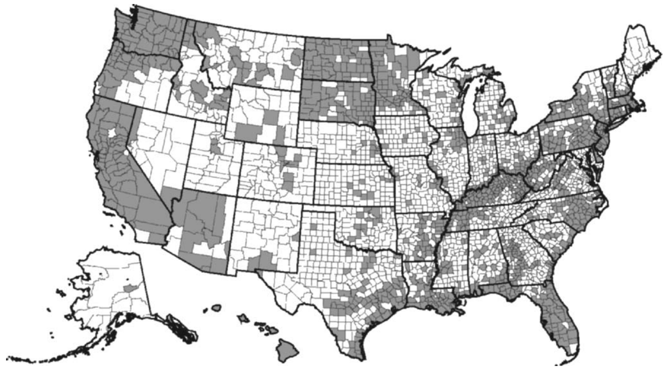

Fig. 1. Nationwide availability of Q3 flood data. Counties with Q3 flood data are highlighted in gray (Source: FEMA ⟨http://www.msc.fema.gov/datafls/allq3list.shtml⟩, status as of November 26, 2003).

delineation tool for flood boundaries for individual parcels of land (FEMA 2006a). Unfortunately, Q3 data are not available nationwide. Only forty percent of all U.S. counties possess Q3 data, though they are among the most populous and represent 75% of all U.S. households (FEMA 2003a) (Fig. 1).

In 2003, FEMA acknowledged the limitations of the hard copy FIRMs and initiated an ambitious map modernization program, including updating paper FIRMs to digital FIRMs (DFIRMs). A DFIRM includes all the information of a FIRM (graphics, text, base map information, etc.). The process of creating DFIRMs not only includes moving from hard copy to digital forms, but also involves the revision and update of flood risks. It is generally performed by incorporating improved information such as digital elevation models derived from light detection and ranging systems (LIDAR) or automated hydrology and/or hydraulics techniques (e.g., HEC-GeoHMS, HEC-GeoRAS, MIKE 11) to spatially delineate flood zones (FEMA 2006b).

Thus far, the map modernization process has been very slow and hampered by program deficiencies such as missing accuracy standards and lack of quality control (General Accounting Office 2004). As pointed out by the General Accounting Office's Report, a major deficit is that "FEMA has not yet developed a clear strategy for partnering with communities that have few resources, limited mapping capability, and little history of flood mapping activities." As a result, DFIRMs only exist for a very small number of communities (e.g., three counties out of 46 in South Carolina possess DFIRMs), so that FIRMs and Q3 flood data are still the standard planning tools for communities when it comes to delineating flood zones.

Mapping Flood Hazards

Existing Models

Crucial to the accuracy of floodplain modeling are, in short, a suitable hydrology and hydraulics (H and H) model and input data for the model. Generally, there are trade-offs between the sophistication of the model and the amount of input data required. Detailed models usually rely on extensive input data and produce accurate outputs while simplified models trade little data for less accurate outputs (Bates and De Roo 2000). The two approaches presented here fall into the latter category.

Traditional floodplain mapping techniques require a considerable amount of input information on hydrologic, hydraulic, and topographic parameters. Key data sources for hydrologic analyses—and hence for flood frequency and base flood analyses—are stream gauge data. Whenever such data are absent as is the case for many rural streams, probabilistic methods are employed to estimate stream gauge data. Hydrologic outputs are then combined with information on stream cross sections, land use, obstructions (e.g., bridges, levees, etc.), and so forth to assess flow dynamics and develop water surface profiles. Based on these parameters, numerical and aspatial hydraulic models turn flood flows into hydrographs, which are estimates of discharge and water surface elevation at a specific location (Dodson and Li 1999; Krpo 1999; De Roo et al. 2000; Shamsi 2002).

There are numerous H and H software products on the market that facilitate the calculation of discharge estimates and water surface profiles. Key differences between these products lie in (1) their algorithms such as one-dimensional flow models (MIKE11, HEC-RAS, LISFLOOD-FP, ONDA, ISIS) versus two-dimensional flow models (MIKE21, TRIMR2D, TELEMAC-2D); and (2) the size of the study area/reach length that can be investigated (De Roo et al. 2000; Horritt and Bates 2002; Jones et al. 2002).

In order to spatially visualize the extent of flood inundation, discharge estimates, and water surface elevations are overlaid onto terrain models or topographic maps (Jones et al. 2001). For example, geographic information systems (GIS) and the integration of more detailed digital elevation models (DEM) into floodplain modeling have significantly improved the process, user friendliness and spatial accuracies of floodplain mapping (Jones et al. 2001; Shamsi 2002; Wang et al. 2002; Wang and Zheng 2005).

Over the past years, major GIS vendors upgraded standard GIS software packages with H and H modeling features (e.g., GIS Stream Pro for ArcView, ArcHydro Tools for ArcGIS) (Dodson and Li 1999; Shamsi 2002). At the same time, the hydrologic community added GIS features to H and H software to support geographic datasets such as DEMs that enable a spatial representation of flood inundation (e.g., MIKE 21, HEC-GeoRAS) (Kraus 1999; Shamsi 2002). These developments improved the interchangeability of data in both directions significantly.

Besides commercial GIS vendors, governmental agencies are actively involved in the development of integrated GIS tools for flood management. FEMA has expanded its loss estimation tool (HAZUS-MH, short for Hazards U.S. Multihazard) to include flood and hurricane hazards in addition to the earthquake module. The most current release of HAZUS-MH MR1 operates on the ArcGIS 9.0 platform and requires the spatial analyst extensions. For the flood module, HAZUS-MH has the capacity to delineate the flood hazard, produce flood depths and assess flood losses. Little has been published, to date about its flood modeling and flood loss estimation capabilities (Scawthorn et al. 2006a,b).

In addition to FEMA, the U.S. Geological Survey (USGS) has developed GIS-based flood monitoring software that also possesses floodplain-mapping capabilities. The USGS cooperates with the National Oceanic and Atmospheric Administration (NOAA), the U.S. Agency for International Development (USAID), and Famine Early Warning System Network (FEWS NET) to examine remote sensing and GIS tools for flood monitoring in developing countries (UNEP 2002). An outgrowth of this effort is the stream flow model (SFM), which is operational in the Limpopo River Basin, Mozambique (Uhlir 2003). The software is widely used by FEWS NET in cooperation with partners in data poor environments and developing countries—most cur-

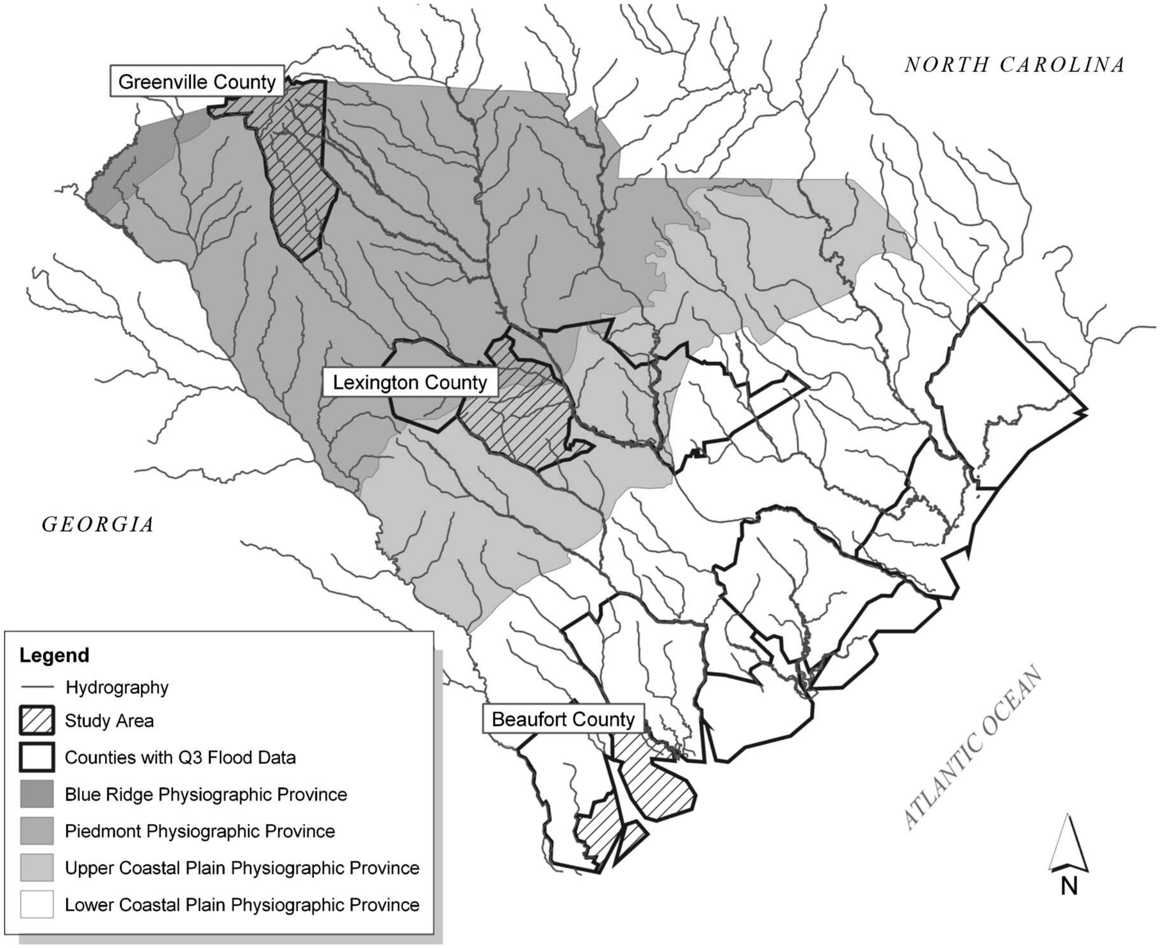

Fig. 2. Overview of the hydrography and physiography of South Carolina as well as the availability of Q3 flood data for the state

rently in Asia (UNEP 2002). Within the United States, however, the software has not been tested in regard to its applicability for mitigation efforts at the local level, despite its ease of use and small number of required input data sets.

Alternatives in Data Poor Environments

The lack of adequate data for flood hazard mapping is most pronounced in rural areas throughout the United States (Fig. 1). In South Carolina, for example, only 12 of the 46 counties have Q3 data: those along the coast, which are subject to hurricane-induced coastal flooding, and the most populated inland counties (Fig. 2). When compiling hazards assessments in response to the Disaster Mitigation Act of 2000, thirty-four counties lacked basic spatial information on their flood hazards. This is not a unique situation as Fig. 1 aptly illustrates, especially in the less populated counties of the country.

The most simplistic solution would be to buffer the stream network and assume that flooding would occur at some constant distance (say 50 m) from the stream centerline for a 1% chance flood. While procedurally easy to do, there is little scientific support for doing so. Topography is an important element in flood zone delineation and to assume a uniform flood height based on distance from the stream would be erroneous.

To address the problem besides using highly sophisticated flood models, we compared the modeling capacities of SFM 3.3 and HAZUS-MH for three test counties in South Carolina and judged it against the Q3 data for each to see which model provided the best approximation. The goal was to develop a relatively simple "work around" for those counties who did not have Q3 or DFIRM data so that emergency planners would have some flood hazard information in order to complete their all-hazards assessments and subsequent mitigation plans. If the proof of concept works and we can determine the model that best mimics the Q3 data, then it could then be rerun for the remaining 34 counties with South Carolina, thus providing at least some robust initial assessment of the flood hazard zones. Whenever resources are available, these assessments should be subsequently replaced by more sophisticated flood risk studies.

The writers acknowledge the fact that the benefits of user-friendly and interface-based flood model/GIS could sacrifice the accuracy of flood modeling outputs. The inexperienced user might over rely on default model parameters and neglect or even ignore the limitations of modeled results. Therefore, it is even more important to continually test and evaluate the accuracy of integrated models such as HAZUS-MH (Level 1 analyses) and SFM.

Study Area

The study area for this research includes Greenville, Lexington, and Beaufort counties in South Carolina (Fig. 2). These three counties are located in the three major physiographic provinces in the state: The Blue Ridge Mountains and Piedmont (Greenville

County), the upper coastal plain (Lexington County), and the lower coastal plain (Beaufort County) (Kovacik and Winberry 1989). The land-surface elevation of Greenville County ranges from 700 to 3,300 ft above sea level. Moderate to poor infiltrating soils characterize the hydrography and precipitation tends to run off rapidly into stream channels. Lexington County, situated in the upper Coastal Plain, has an undulating terrain that lacks distinct riverine valleys. Elevations are generally less than 700 ft above sea level and extensive swamps and floodplains are typical. Coastal Beaufort County features small, meandering stream drainage patterns with relatively flat terrain between sea level and 42 ft above sea level. Soils are sandy and highly permeable (Feaster and Tasker 2002).

Payments made through the National Flood Insurance Program (NFIP) for insured losses in South Carolina amounted to $423 million (1978–2004). This places the state seventh in the nation in total insured flood loss payments after Texas, Florida, Louisiana, North Carolina, New Jersey, and Pennsylvania (FEMA 2006c). Nationally, the average payment per claim was $10,868, but in South Carolina it was much higher ($15,851). From 1978 to 2004, the NFIP issued approximately $190 million as loss compensation to Charleston County alone and paid more than $139 million to Horry and $76 million to Georgetown County. In terms of rankings by damage amounts, this places Beaufort and Greenville County far behind, with flood loss claims at around $5 million within South Carolina (FEMA 2006c).

Methodology

The modeled output of floodplain delineations of both SFM 3.3 and HAZUS-MH were compared to the Q3 data (and DFIRMS where available) for the three county South Carolina study sites—Greenville, Lexington, and Beaufort. We recognize that the comparison of two models on three watersheds in one state is limited, but our goal was to establish the proof of concept, not provide a definitive assessment of model performance.

Brief Synopsis of Flood Models

SFM 3.3 is a physically based semidistributed hydrologic model (Artan et al. 2002) and was developed as an extension to GIS-based software (ESRI's ArcView 3.x). It is first and foremost a flood-monitoring tool with precipitation and evaporation data as the most important inputs to the model. The model allows though for simple floodplain mapping based solely on a DEM as input data, from which all H and H parameters are estimated since SFM 3.3 lacks a default database on basic H and H parameters.

To generate flood boundaries, SFM 3.3 requires the DEM-derived H and H parameters plus user-provided flood height information. The flood height information provided by the user is assumed to be geographically uniform and not location specific. Basic hydraulic geometry in the downstream direction tells us that mean flow depths of bank-full discharge all increase in the downstream direction as a power function of the overall discharge. This is also true of the drainage area.

SFM is a physically based hydrologic model designed for flood monitoring, not floodplain mapping. As such, its utility for this application is somewhat problematic because in the original design, many of the H and H processes are bypassed due to the assumption of uniform flood heights throughout the model. While the assumption of a uniform flood height is overly simplistic (and recognized), it does provide a very crude approximation of flood extent, especially when little other hazard information is available. SFM cannot and should not substitute for reliable floodplain delineations with localized stream gauge data and detailed H and H analyses.

HAZUS-MH is also a GIS-based model and operates on ESRI's ArcGIS 8.0 and requires the Spatial Analyst extension. The most current release of HAZUS-MH MR 1 operates on ArcGIS 9.0. The main purpose of HAZUS-MH is to estimate losses from natural hazards (first earthquakes, then wind and flooding) by integrating building and lifeline inventory databases, physical processes (ground motion, flooding, wind), building and lifeline engineering damage models, direct and indirect economic loss models, and casualty assessment into one application. The intent was to provide a general loss estimation tool for use in hazards management including preparedness and mitigation (Schneider and Schauer 2006).

HAZUS-MH offers three levels of analysis for flood hazards ranging from generalized overviews (Level 1) to very detailed and data intensive analyses (Level 3). Level 1 requires minimal user and data input with a high degree of automated analysis. A user with detailed local knowledge is encouraged to supply HAZUS with information through the FIT interface (flood information tool) and perform a more detailed Level 2 analysis. Level 2 analyses require flood surface data (e.g., digital base flood elevation lines from FIRMs), digital floodplain boundaries (e.g., from DFIRMs or Q3 data), and digital ground elevation data.

The first level of analysis is the most general but also the least resource intensive in terms of local flood data and GIS knowledge requiring only a DEM as user-provided input (FEMA 2003b). This paper only explores the floodplain-modeling capabilities of HAZUS-MH at the first level of analysis. It should be noted that at the Level 1 analysis, HAZUS-MH performs H and H analyses based on a default database including regional hydrologic regressions and gauge data (total and contributing drainage area; mean, standard deviation, and skew coefficient of flood frequency curve) (FEMA 2003b). For more information on the flood modeling methodology of HAZUS-MH see Scawthorn et al. (2006a,b).

Modeling Process and Inputs

The methodology used in the modeling and assessment process is shown in Fig. 3. Both models required a digital elevation model (DEM) as the initial data input. The online USGS Seamless Data Distribution System supplied the 30 m resolution DEM (one-arc-second National Elevation Dataset). The 30 m resolution DEM is the standard input for HAZUS-MH and is generally adequate, though in low-relief areas such as costal plains the DEM's vertical and horizontal resolution tends to be insufficient for South Carolina.

HAZUS-MH and SFM 3.3 depend strongly on the quality of the input DEM. By providing a high-resolution DEM, the user can positively influence the accuracy of the modeled floodplain extent. This is basically the only opportunity for users of both models to modify and influence the H and H analysis and modeling process. At analyses levels higher than Level 1 though, such as Level 2 using the flood information tool (FIT), HAZUS-MH allows and actually forces the user to provide detailed hydrologic and hydraulic data, which ultimately will improve the modeling output. However, for our purposes we are assuming a data poor environment in combination with inexperienced users.

The initial analysis steps in HAZUS-MH (Level 1) and SFM 3.3 are basically the same and simulate the virtual path of water across the DEM. Both models directly draw on the DEM to gen-

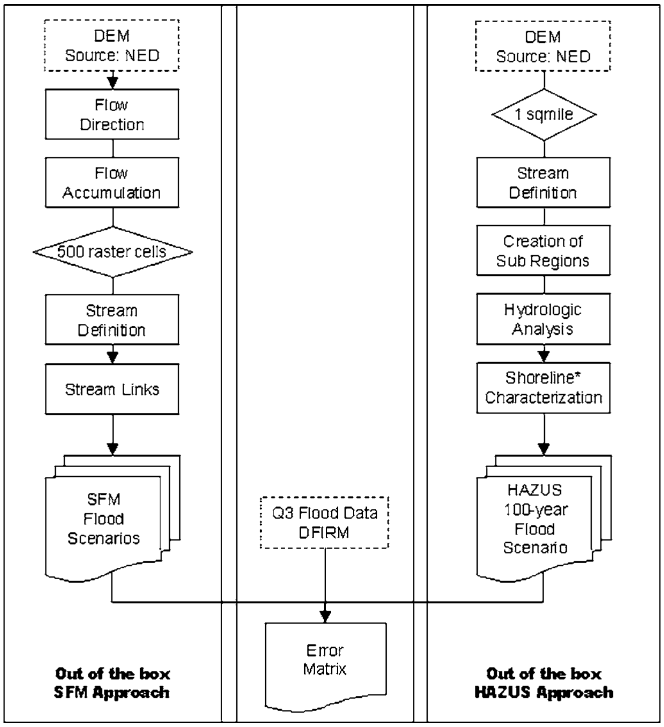

Fig. 3. Flow chart of the floodplain modeling and assessment process

erate intermediate hydrologic datasets: (1) flow direction grid, which contains information on the direction in which a DEM raster cell discharges all its water; (2) flow accumulation grid, which represents the number of upstream cells draining through a raster cell; (3) stream network grid, which contains a value of “1” for all raster cells in the flow accumulation dataset that have a value above a specified threshold; and (4) stream links grid, which is derived from the stream network and include a unique identifier for each stream segment.

HAZUS-MH and SFM 3.3 slightly differ in the way they determine a stream network: SFM 3.3 bases networks on stream length whereas HAZUS-MH is driven by the size of the drainage area. During the hydrologic analysis process in HAZUS-MH, the software asks the user for a threshold to initiate a stream. The lowest threshold for stream initiation is one square mile ($2.59\ km^2$); in other words, a collection of cells that drain an area of one square mile or more are considered a stream (FEMA 2003b). SFM’s threshold for stream initiation is not related to the size of drainage areas but rather to the length of a stream. SFM 3.3 only initiates streams with at least 500 raster cells equivalent to 15 kilometers when using a 30 meter resolution DEM, i.e., SFM 3.3 simplifies the stream network significantly.

SFM 3.3 models flood extent based on a uniform flood height value that is applied across the whole study area. This approach contrasts HAZUS-MH, which draws on an internal H and H database to model both flood extent and place-specific flood heights. Another difference between SFM 3.3 and HAZUS-MH is related to costal floodplain modeling: HAZUS-MH requires detailed information on shoreline characteristics such as exposure and geophysical aspects. In our proof of concept, we derived this information from land use/land cover data and satellite imagery available online from the USGS seamless data distribution system. A secondary data input was the 100-year still water elevations. These were obtained from flood insurance studies that were accessed online at the FEMA map store at ⟨http://store.msc.fema.gov⟩. These inputs were not required for SFM 3.3.

Accuracy Assessment of Modeled Flood Zones

The accuracy of the modeled flood zones was assessed through the use of error matrices (Table 1), Kappa analysis, and the percentage of overlap between the modeled floodplain and Q3/DFIRM floodplain—our standard. Error matrices and Kappa analysis are common approaches in the field of remote sensing for accuracy assessment purposes (Jensen 2005). This procedure was done for both the HAZUS-MH and SFM 3.3 models.

We derived the following information from the error matrix: Classification accuracy (or overall accuracy), errors of omission, errors of commission, and the Kappa coefficient. Classification accuracy was calculated by summing correctly classified 100-year floodplain cells and correctly classified non-floodplain cells and dividing them by the total number of raster cells. Errors of omission captured a model’s failure in identifying the 100-year floodplain (Type II error) whereas errors of commission included falsely modeled flood zones, i.e., not identified by the reference data (Type I error). The Kappa coefficient—ranging from zero to one—represented a statistic of agreement between modeled 100-year floodplains and reference data (Q3).

In cases where the number of observations (pixels) in one classification category is much larger than in the other, classification accuracy can be a misleading measure of accuracy. Therefore, the Kappa coefficient is oftentimes a more meaningful measure revealing strengths and weaknesses of the tested models. Kappa coefficients that are higher than 0.80 indicate strong agreement between model and reference data, values between 0.40 and 0.80 show moderate agreement, and coefficients below 0.40 represent weak agreement (Landis and Koch 1977). For the comparative assessment in Lexington County, we excluded Lake Murray (an artificial lake) from the study area because the HAZUS-MH algorithm could not capture the geometry and drainage of the lake correctly.

HAZUS-MH showed better classification accuracy (or so-called overall accuracy) ranging from 92.1% in Beaufort County to 93.8% in Greenville County (Table 2). SFM 3.3 was weaker in its performance with classification accuracy between 82.4% in Beaufort County to 88.2% in Greenville County. In a small sensitivity test using a 10 m resolution for Greenville County, both models achieved their highest classification accuracy (94.5% for HAZUS-MH, 91.7% for SFM 3.3).

As previously mentioned, classification accuracy can be a misleading measure based on the number of observations, so it was

Table 1. Logic of the Error Matrix Used to Assess the Accuracy of HAZUS-MH Outputs

Criteria	Number of cells classified as 100-year floodplain in HAZUS-MH	Number of cells classified as nonfloodplain in HAZUS-MH
Number of cells classified as 100-year floodplain in Q3 flood data	=correctly modeled cells	=incorrectly modeled cells
Number of cells classified as nonfloodplain in Q3 flood data	=incorrectly modeled cells	=correctly modeled cells

Table 2. Accuracy Results for Greenville, Lexington, and Beaufort Counties (30 m Resolution DEM) When Compared to Q3 Flood Data

Study area	Accuracy compared to Q3	HAZUS-MH	SFM 3.3
Greenville County[a] (30 m resolution DEM)	Overlap between Q3 and model	42.01%	42.17%
	Kappa coefficient[c]	0.46	0.27
	Classification accuracy[d]	93.84%	88.18%
	Error of omission[e]	41.05%	72.19%
	Error of commission[f]	58.00%	57.83%
	Uniform flood height[g]		6 meter
Lexington County[b] (30 m resolution DEM)	Overlap between Q3 and model	30.23%	47.81%
	Kappa coefficient	0.36	0.39
	Classification accuracy	92.30%	90.14%
	Error of omission	43.20%	58.25%
	Error of Commission	69.77%	52.19%
	Uniform flood height		2 m
Beaufort County (30 m resolution DEM)	Overlap between Q3 and model	98.32%	72.07%
	Kappa coefficient	0.79	0.50
	Classification accuracy	92.12%	82.35%
	Error of omission	8.57%	17.05%
	Error of commission	1.68%	4.88%
	Uniform flood height		3 m
Greenville County[b] (10 m resolution DEM)	Overlap between Q3 and model	48.22%	64.08%
	Kappa coefficient	0.52	0.48
	Classification accuracy	94.46%	91.73%
	Error of omission	35.59%	55.86%
	Error of commission	51.78%	35.92%
	Uniform flood height		2 m
	Accuracy compared to DFIRM	HAZUS-MH	SFM 3.3
Lexington County[b] (30 m resolution DEM)	Overlap between DFIRM and model	30.25%	49.21%
	Kappa coefficient	0.35	0.39
	Classification accuracy	92.52%	90.32%
	Error of omission	48.33%	60.64%
	Uniform flood height		2 m

[a]The input DEM was hydrologically corrected for SFM 3.3.

[b]The input DEM was hydrologically corrected for SFM 3.3; the area of Lake Murray was excluded from the study area.

[c]Kappa coefficient: Statistic of agreement between modeled flood maps and reference data.

[d]Classification accuracy equals the sum of correctly classified flood cells and correct nonflood cells divided by the total number of raster cells.

[e]Error of omission: Model fails to identify the 100-year floodplain (Type II error).

[f]Error of commission: Flood zones are erroneously identified in areas that are actually outside the 100-year floodplain (Type I error).

[g]Uniform flood heights were applied across the study area to model the 100-year floodplain extent. Numerous scenarios were generated with varying flood heights. The scenario presented in the table showed the lowest Kappa coefficient out of all scenarios and also visually matched Q3 data the closest.

important to also look at the Kappa coefficients and the match between real (reference standard, Q3) and modeled floodplains. HAZUS-MH modeled coastal 100-year floodplains very well with a match of 98.3% between its output and Q3 flood data and a Kappa coefficient of 0.79. HAZUS-MH performed moderately well in the Piedmont region of Greenville County with 42% overlap (Kappa coefficient=0.46). However, HAZUS-MH performed less well in Lexington County in the upper coastal plain with floodplain overlap of less than one-third (30.2%) and a Kappa coefficient of 0.36 (Q3). This is the smallest amount of overlap found in any study area or model.

SFM 3.3 also performed best in coastal Beaufort County, with an agreement of 72.1% between its output and Q3 flood data and a Kappa coefficient of 0.50. SFM 3.3 performed as well as HAZUS-MH in the Piedmont region (Greenville County) delineating 42% of Q3 floodplains although the Kappa coefficient was less (0.27 compared to 0.46). Finally, in the upper coastal plain region, SFM 3.3 was much better than HAZUS-MH matching 50% of Q3 (Kappa coefficient=0.36) floodplain in Lexington County.

In Lexington County, we had both Q3 and DFIRM data, so we briefly examined the overlap in our reference standard. The Kappa coefficient between the reference data—Q3 flood data and DFIRM—was only 0.87, and the Q3 floodplains and DFIRM floodplains overlapped at only 89%. The area identified as 100-year floodplain in Q3 decreased from 185 to 179 km^2 in the new DFIRM. However, this did not significantly influence the classification accuracy or Kappa coefficients of HAZUS-MH or SFM 3.3 in Lexington County when compared to either reference data source. Thus, we conclude that there were no significant differences when using Q3 flood data or DFIRM as the reference standard. However, other research suggests that updating from FIRM to DFIRM could result in substantially different 100-year floodplain boundaries (Aycock and Wang 2004; General Accounting Office 2004).

Table 3. Areal Extent of Floodplain Delineations (km^2). Overpredictions Greater Than 10% Are in Bold; Underpredictions Greater Than 10% Are in Bold Italics.

Study area[a]	Q3 (standard)	HAZUS-MH	SFM 3.3
Greenville County (upland)	203	***145***	**308**
Lexington County	199	***106***	**228**
Beaufort County (coastal)	1,765	1,898	***1,533***

[a]All outputs are based on a 30 m DEM.

Determining Model Effectiveness for Mitigation Planning

There are four primary areas of comparison that were used to evaluate the effectiveness of the two models. These include the estimation of floodplain extent, quality of required input data, quality of intermediate datasets, and hardware and software restrictions.

Over- and Underestimation of Floodplain Extents

HAZUS-MH consistently exhibited higher classification accuracies than SFM 3.3 in each of three test sites. While classification accuracy is not the sole indicator of the quality of modeled output, it is important to understand what influences the classification accuracy. For example, the modeling algorithms of HAZUS-MH tie the existence of floodplains to streams and prevent the generation of data artifacts such as floodplains not connected to a stream (e.g., a lake or pond feature). This means that HAZUS-MH is prone to underpredicting 100-year floodplains in upland or undulating terrain (Table 3) [Fig. 4(a)]. This shortcoming cannot be manipulated at the first level of analysis in HAZUS-MH. The software draws only on the input DEM and on an inherent database that includes USGS regression equations and gauge records to create discharge frequency curves (FEMA 2003b). Thus in order to model noncoastal floodplains more accurately in HAZUS-MH, the user would need to proceed to analysis Level 2 and manipulate local data via the FIT tool (FEMA 2003b).

SFM floodplain models show errors in area delineated as floodplain that are opposite to HAZUS-MH. The simplicity of the algorithm behind SFM 3.3 lacks the capability to tie floodplains to streams. Consequently, the model generates artifacts such as floodplains not attached to a stream or flood zones at the head of streams. This causes SFM 3.3 to significantly overpredict [Fig. 5(b)], especially in upland environments. For instance, in Greenville County with significant topographic relief, the model (30 meter resolution DEM) when compared to Q3 data overestimated flood zones by 52% (308 versus 203 km^2). Most of the overprediction was caused by such artifacts. Data postprocessing could eliminate this problem since these artifacts can be visually identified without any problem.

In coastal areas, HAZUS-MH slightly overpredicts the area of floodplains (7.5%) [Fig. 5(a)], while SFM underpredicts (by 13%) [Fig 4(b)]. Again, this discrepancy in modeled extent is due to the different approaches implemented in HAZUS-MH to model riverine versus coastal floodplains. Modeling coastal floodplains requires detailed, manually entered, and user-provided information whereas riverine floodplains are generated without any user interaction. For coastal floodplains HAZUS-MH asks for additional information: Base flood elevation, dune morphology, wave run up, wave height, and still-water elevations. Not surprisingly such in-depth information allows HAZUS-MH to model coastal floodplains almost identical to Q3 flood data with an overlap between both datasets of 98.3% (Kappa coefficient=0.79). However, the assignment of 100-year still-water elevations was not without problems and can be a source for user errors. For instance in Beaufort County, the flood insurance studies determined a coastal segment and its corresponding still-water elevation through descriptive information—e.g., "In the vicinity of Buzzard Island"—instead of through geo-referenced coordinates. This made identifying the described coastal segment and assigning its appropriate still-water elevations very difficult.

The absence of local modeling algorithms, internal hydrologic and hydraulic databases, and specific coastal parameterization as in HAZUS-MH appear to influence the divergent modeling outcome in the areal extent of the floodplain. In the aggregate, HAZUS-MH provided the closest approximation to Q3 (less than 1% difference in total area delineated for all study counties). SFM underpredicted the total area by 4.5%.

Quality of Input Data: Topographic Relief

Both models reached their highest classification accuracy in Greenville County based on a 10 m resolution DEM—though not their highest Kappa coefficients. When compared to the Kappa coefficient for the 30 m DEM for Greenville, there was a slight increase for HAZUS-MH (0.45–0.52) and a significant improvement for SFM 3.3 (0.27–0.48) when the quality of the DEM was improved to the 10 m resolution (Table 2).

The improvements of the Kappa coefficient of SFM 3.3 can be attributed to a significant decrease in errors. The error of omission dropped from 72 to 56% and the error of commission declined from 58 to 36%, while the match between Q3 flood data and the SFM 3.3 output increased from 42 to 64%. Thus, SFM 3.3 performed better than HAZUS-MH with a match between its model and Q3 of 64% even though its classification accuracy and Kappa coefficient are below those of HAZUS-MH, which match Q3 flood data with only 48%.

The results for Greenville County indicate that the accuracy of modeling outputs is likely to increase with a higher resolution DEM. However, the consistent integration of a high-resolution DEM into HAZUS-MH does have some problems, especially when rivers form county boundaries. This is because HAZUS-MH always requires a DEM beyond the borders of a study area in order to capture the watersheds of the intended study area sufficiently. In instances where a high-resolution DEM is only locally available, the user is required to fulfill the HAZUS DEM requirements through a combination of high- and low-resolution DEMs. For example, a 10 m resolution DEM was not available beyond the county borders of our study site, Greenville County. Therefore, we were forced to combine the 10 m resolution DEM with the 30 m resolution DEM (beyond county border) to fulfill the HAZUS-MH requirements. SFM 3.3 does not have such requirements, so we used the smaller 10 m resolution DEM covering only Greenville County for that model run.

Quality of Intermediate Datasets

Both software models have deficiencies in deriving an adequate stream network from the input DEM. For the study areas analyzed here, the one square mile threshold for stream initiation in HAZUS-MH was too high. Compared to the river reach data by the Environmental Protection Agency, HAZUS-MH did not identify small tributaries or shortened the run of streams in many cases. Hence, HAZUS-MH failed to generate a realistic stream network for South Carolina. In SFM, the minimum threshold for

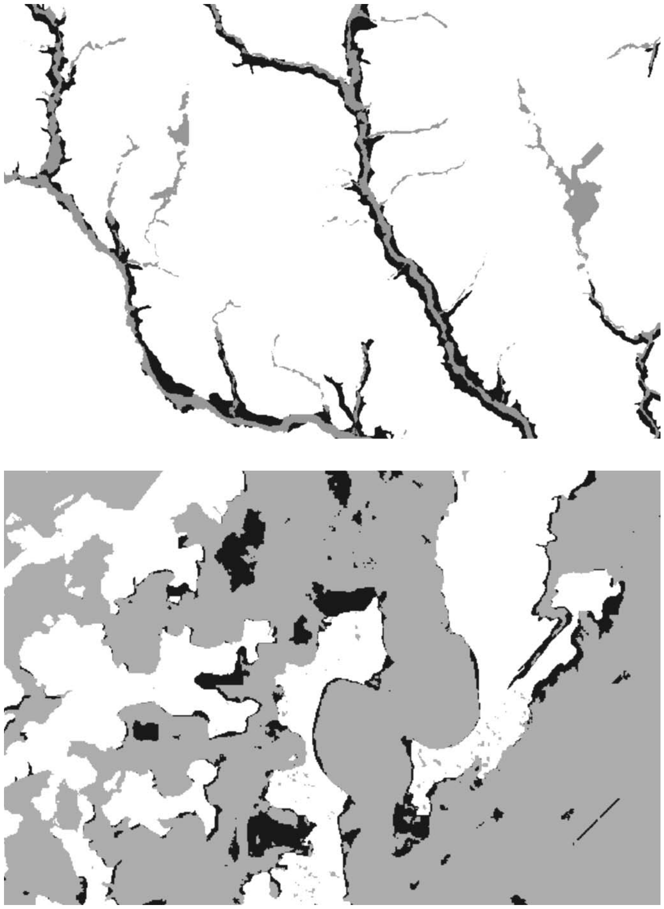

Fig. 4. (a) and (b) underprediction of 100-year floodplains using 30 m DEMs. Fig. 4(a) shows parts of Lexington County, where HAZUS-MH (gray) underestimates the Q3 floodplain (black). Fig. 4(b) represents an area in Beaufort County, where SFM 3.3 (gray) underpredicts the Q3 floodplain (black).

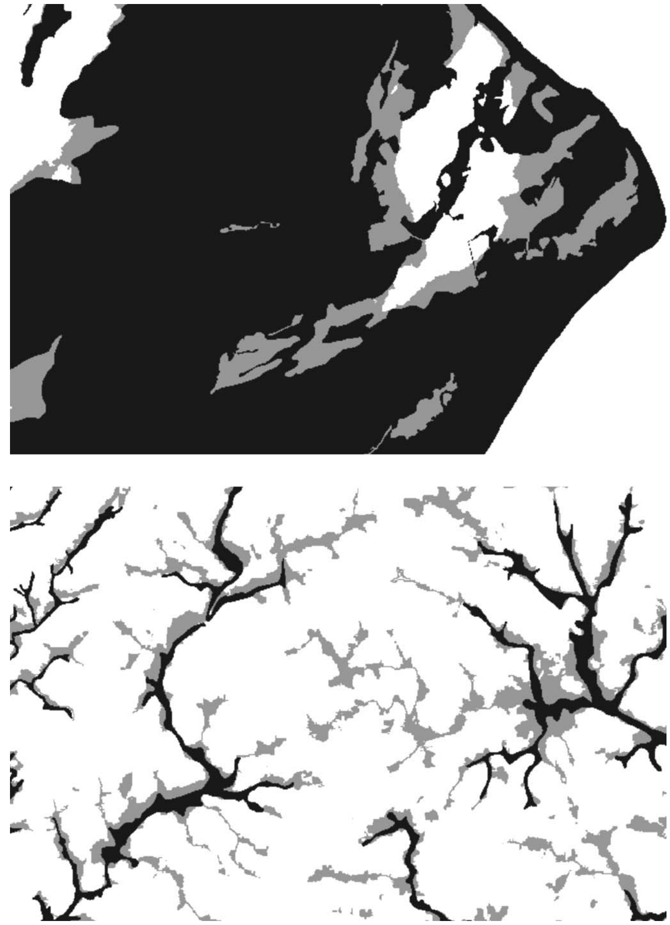

Fig. 5. (a) and (b) overprediction of floodplain delineation from modeled output using 30 m DEMs. Fig. 5(a) shows parts of Beaufort County, where HAZUS-MH (gray) overestimates the Q3 floodplain (black). Fig. 5(b) represents an area in Lexington County, where SFM 3.3 (gray) overpredicts the Q3 floodplain (black).

stream initiation (at least 500 raster cells or 15 km of stream length for a 30 m DEM) is also too high to derive a realistic stream network for large-scale studies at the county level or below.

There are two options to resolve this issue: First, by correcting the input DEM for hydrology; and second, by importing a stream link dataset generated outside of HAZUS-MH and SFM 3.3. However, the second option is only applicable to SFM 3.3 since the incorporation of external datasets into HAZUS-MH (at the analysis Level 1) is difficult due to its highly automated approach.

To generate an external stream link dataset, we used HEC-GeoHMS by the Army Corps of Engineers, which is an extension to ArcView 3.x. HEC-GeoHMS requires only a DEM as the initial input dataset. Intermediate datasets on flow direction, flow accumulation, and stream definition are the same as in SFM 3.3. A stream initiation threshold of one square kilometer was sufficient to closely model South Carolina's hydrography at about a scale of 1:24,000. This dataset was then easily incorporated into SFM 3.3.

The possibility of correcting a DEM for hydrology is not implemented in either modeling software. Hydrologic correction or so-called reconditioning of a DEM includes the manipulation of the DEM wherever there is a mismatch between the DEM and a hydrography reference dataset. In other words, the flow direction and location of streams is reinforced wherever the DEM shows discrepancies to the reference data. This procedure ensures that the stream network extracted throughout the modeling process matches the location of the real-world stream network as closely as possible. Even though hydrologic correction is essential to successful floodplain modeling, the process remains problematic because it can introduce errors into the DEM by (a) raising the elevation of stream surrounding cells too much so that water is drained downstream instead of horizontally into adjacent floodplains, or (b) introducing (artificial) parallel streams if the locations between the stream in the DEM and the reference data are outside a specified buffer (Hellweger and Maidment 1997).

Whenever the quality of the DEM is insufficient—its capability to depict the real-world hydrography—hydrologic correction is crucial for successful floodplain modeling. In South Carolina, hydrologic correction was necessary since large portions of the National Elevation Dataset (NED) showed relatively poor elevation data quality (e.g., low vertical accuracy). The publicly available one-arc-second NED for South Carolina is a DEM that is mostly derived from Level 1 and Level 2 (30 m resolution) data (95%), with only 5% derived from 1/3-arc-second (10 m resolution) data (U.S. Geological Survey 2001). The overwhelming percentage of lower quality elevation data runs counter to the nationwide quality status of NED (Hodgson et al. 2003). As reported in the NED Release Notes of June 2004, the amount of

Level 1 data nationwide has dropped to about 7%, the percentage of Level 2 data decreased to 45%, and the use of 1/3-arc -second (10 m) data has increased to about 48% for the conterminous U.S (U.S. Geological Survey 2004). Obviously, this was not the case for South Carolina.

HAZUS-MH performs its analysis (at the first level of analysis) without hydrologically correcting the DEM, without allowing the user to manipulate any of the intermediate datasets, and without any visible output to the user except the final stream network. Even though both HAZUS-MH and SFM possess the possibility to fill sinks—cells that are lower than all surrounding cells, i.e., they trap the flow of water—this step is not equivalent to hydrologic correction nor is it sufficient. Without a hydrologically corrected DEM, HAZUS-MH runs the risk of misrepresenting the location and flow direction of streams. Additionally, with the software's high threshold for stream initiation, HAZUS-MH artificially shortens the lengths of streams, especially tributaries. These are possible explanations for HAZUS-MH's weak performance and underprediction of 100-year floodplains in noncoastal areas.

The better performance of SFM 3.3 in the upland counties can be attributed to the use of a hydrologically corrected DEM. For hydrologic correction, the researchers used the freely available HydroTools extensions for ArcGIS 8.3 and higher. The correction of the DEM required a vector hydrography data layer depicting correct location and course of a stream. The River Reach files of the Environmental Protection Agency served as vector hydrography data and were downloaded from the USGS National Hydrography Dataset (NHD) available at ⟨http://nhdgeo.usgs.gov/viewer.htm⟩. The correction involved superimposing the River Reach dataset onto the raw DEM and burning it into the DEM. This step slightly raised the elevation of cells—within a 300 m (10 cells) buffer around the NHD stream—that did not coincide with the NHD stream network. Therefore, the stream network modeled by SFM 3.3 closely resembled the real stream network of South Carolina. Ultimately, this step represents a trade-off between spatial accuracy and the risk of altering elevation and maybe floodplain boundaries. Prior to the reconditioning of the DEM though, extensive manual editing of the vector hydrography data layer was necessary. Coastlines and outlines of lakes and rivers had to be deleted to avoid the introduction of artificial streams into the DEM. The DEM for Beaufort County was not corrected because reconditioning of an area with barely any relief would have introduced additional and erroneous drainage patterns.

Hardware and Software Restrictions

The use of digital elevation models—especially high resolution DEMs—demands high-end hardware components. According to FEMA, the preferred hardware requirements for HAZUS-MH are: a 2.6 gigahertz processor, 512 megabyte of RAM, 80 gigabyte of free hard disk space, and a DVD-ROM drive (FEMA 2003b). The writers performed their HAZUS-MH analyses on a computer with a 3.4 gigahertz processor, two gigabyte of RAM, and more than 150 gigabyte of free disk space. This is much higher than the HAZUS-MH recommendations but obstacles were still encountered, slowing down the analysis process. These issues were primarily software-related.

HAZUS-MH builds on ArcGIS 8.3, which cannot process raster files larger than 2.147 gigabytes, thus all input as well as intermediate datasets must be smaller than this in order for the modeling process to run successfully. The reason why HAZUS-MH creates large files is related to the storage of raster files as floating point data and not as integer grids. Floating point values show decimal accuracy whereas integer values are whole numbers. Naturally, floating point representation is most appropriate for elevation data. However, the extremely large files created by floating point data are very problematic wherever software products limit file sizes to 2.147 gigabyte.

Due to this limitation, a 5 m resolution DEM for Greenville County could not be used since the DEM exceeded the 2.147 gigabyte limit. The release of HAZUS-MH MR1 (built upon ArcGIS 9.0) in February 2005 allows processing of files larger than 2.147 gigabyte. Still, large files demand advanced hardware components. Numerous attempts to reduce the study area to the tract or block group level failed because certain tracts of Greenville County included streams with a large drainage area. Consequently, the areal requirements for the DEM at the tract level corresponded to the requirements at the county level, which exceeded the file size limit. A bug in the shell design of HAZUS-MH impeded the creation of study areas at the block group level. According to FEMA's technical support (Pushpendra Johari, electronic mail, March 14, 2005), defining study areas at the block group level works five out of six times, but in our case it never worked. However, it is assumed that similar to the problem at the tract level, certain blocks of Greenville County would have required a spatially large DEM beyond the file size limitations. As a result, we were forced to use a 10 m resolution DEM instead of a more detailed 5 m resolution DEM in order to run HAZUS-MH.

HAZUS-MH is not capable of processing more than 50 streams during the hydraulic analysis (FEMA 2003b). Hence, subsets within the study area have to be created that contain between 30 and 50 streams depending on the resolution of the input DEM. For instance, floodplain mapping in Greenville County based on a 30 m resolution DEM required seventeen subsets with each analysis taking about two to three hours. Based on our experience, the time effort to map floodplains for one county is around one person-week. In contrast, SFM 3.3 generates flood maps for numerous counties within one day.

SFM 3.3 operates with integer grids, which makes the creation of subsets unnecessary. Integer grids have the benefit of smaller files sizes but reduced vertical accuracy. This study mimicked decimal accuracy of a floating point dataset by multiplying all DEMs for use in SFM 3.3 by 100 and converting it into an integer dataset. However, while this approach seems to have worked in noncoastal counties, it is assumed that restricted vertical accuracy of DEMs in SFM 3.3 contributed to the software's weak performance in coastal Beaufort County. Finally, SFM 3.3 is less demanding than HAZUS-MH in terms of hardware requirements. A system with a one gigahertz processor and 512 megabyte RAM is sufficient.

Based on these findings, it is recommended to employ HAZUS-MH for large-scale floodplain modeling with study areas not exceeding a county. Hydrologic analyses using high resolution DEMs should be at the census tract level and below. For crude estimates at smaller scales and in noncoastal areas, SFM 3.3 provides reasonable first approximations (Table 4).

Discussion

More than sixty percent of U.S. counties do not have adequate delineations of floodplains and flood risk and, therefore, must rely on alternative approaches for flood hazards assessment. FEMA's Map Modernization program is a step in the right direction, but

Table 4. Characteristics of Modeling Software

	HAZUS-MH (at the first level of analysis)	SFM 3.3
Hardware requirements	High	Low
Format of raster data	Floating point	Integer
Software requirements	ArcGIS 8.3 or higher and spatial analyst Extension	ArcView 3.x and spatial analyst extension
Option to hydrologically correct a DEM	Missing	Missing
Incorporation of external data	Difficult	Easy
Internal (historic) database	Includes hydraulic unit codes, USGS regression equations and gauge records to estimate discharge frequency curves	Absent
Recommended Application Scale	Large	Small
Possibilities to improve accuracy	Difficult	Fair
Support	Good	Absent
Accuracy	Very good in coastal areas; moderate in noncoastal areas with tendency to underprediction	Fair with tendency of overprediction in noncoastal areas and underprediction in coastal areas

the pace of the remapping effort is very slow. In the interim, communities must still adhere to the hazard assessment and mitigation plans outlined in DMA 2000. In data poor or modeling-inexperienced environments, the analysis of flood hazards is done descriptively, with little or no spatial delineation of flood zones (although a map of stream/river networks might be included).

From a purely technical point of view, HAZUS-MH and SFM 3.3 are suitable workarounds whenever digital flood data are missing. However, HAZUS-MH and SFM are each only suited for certain terrains and scales. The modeling accuracy of SFM 3.3 in coastal areas is unsatisfactory, whereas its performance in noncoastal areas is more promising, but it has a tendency to overprediction. The accuracy of SFM outputs can be improved by postprocessing outputs, employing higher resolution DEM or using site-specific flood heights.

As a surrogate tool for hazard assessment and mitigation planning, the accuracy results of HAZUS-MH are satisfying considering the modeled results are based on the first level of analysis. HAZUS-MH performed particularly well in coastal areas given adequate and sufficient input information from the user. However, the moderate performance in noncoastal areas and its tendency to underestimate floodplains are rather disappointing considering the complex algorithms and databases inherent to HAZUS. Ultimately, accuracy results at the first level of analysis can only be improved by using a DEM of higher resolution than 30 m.

Given more detailed and site-specific input data at the second level of analysis, it is assumed that the accuracy of HAZUS outputs can increase. In order to incorporate locally available flood information at the higher level of analysis though, the user relies on the flood information tool (FIT) to convert user data into HAZUS-readable format. The incorporation of site-specific data on flood heights, floodplain boundaries, etc. requires substantial GIS expertise and is likely to exceed the capabilities of many hazard mitigation planners.

Conclusions

The choice of which approach is best for the community hazard assessment depends on a number of factors. The first is the level of GIS and HAZUS-MH expertise within the local emergency management community. If the expertise is not available locally, then emergency managers must either (1) develop partnerships with local colleges and universities to help assist them, or, more likely; and (2) contract with the private sector to provide such analyses.

A second factor involves setting the tolerable error that the emergency managers are willing to accept. Most of the non-Q3 counties are inland, in areas ranging from gently rolling hills to those with steep topographic relief. Both HAZUS-MH and SFM did not perform well in these environments (with a 30 m DEM), having less than 50% overlap with Q3 data. Instead of a sophisticated (and time-consuming) modeling effort, a decision could be made that a simple buffer along the hydrologic network is all that is required for meeting the intent of the hazard assessment process. However, this process is arguably not suited for serious planning purposes and could be challenged in the hazard assessment.

Third, in landscapes with significantly managed water resources including impoundments (lakes and ponds) the models will not perform well. These so-called artifacts are removable in SFM (they must be done by hand), but are more problematic in HAZUS-MH and would require Level 2 analyses.

Fourth, the use of SFM is hampered by data and software restrictions. For example, there is no institutionalized support for SFM through USGS or FEMA: There is no user's manual, no trouble-shooting hotline either by phone or Internet, nor does USGS promote the software in the United States. This is disappointing given the fact that SFM 3.3 is less resource intensive than HAZUS-MH in terms of time, GIS knowledge, hardware, and software. Also, SFM's capacities and the possibility to generate various scenarios make the software particularly attractive for initial assessments of larger study areas.

Fifth, the demanding hardware requirements for HAZUS-MH restrict its application to an advanced high-end user community. Currently, FEMA reports around 4,200 HAZUS users. Around forty percent of them are local government users (FEMA 2005). This is a fairly low number considering that HAZUS was designed to aid local governments in the process of compiling mitigation strategies. The number of HAZUS users could be increased by improvements in its floodplain modeling capacities such the incorporation of hydrologic correction and the elimination of thresholds for stream initiation to allow large-scale floodplain modeling. Some of these shortcomings have been resolved with the release of HAZUS-MH MR1. Hopefully, continuous improvements of HAZUS, future federal (financial) support for the software, and increasing technical training of emergency managers will establish HAZUS as a true alternative to missing digital flood data and a suitable alternative.

Ultimately, the recommendation for flood zone delineation in a data poor environment ultimately depends on the local resources—time, staff capabilities, financial—the availability of good input data (stream networks, digital elevation models), and the willingness of the emergency managers to improve the quality of their hazard assessments. For some applications, a descriptive narrative may be all that is required. In others, a more detailed delineation is inevitable. This paper presented the strengths and weaknesses of two modeling approaches—HAZUS-MH and SFM. The study is limited insofar as only three study sites were modeled, and should be viewed as a pilot effort rather than an exhaustive assessment. Despite this limitation, the lack of consistent comparative results (to Q3 data—the currently planning standard) should provide an additional impetus to FEMA to speed up their map modernization program, especially for those counties who currently do not have Q3 data.

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References

Artan, G. A., Restrepo, M., and Asante, K. (2002). "A flood early warning system for Southern Africa." *Proc., Pecora 15 and Land Satellite Information 4th Conf.*, ASPRS, Bethesda, Md.

Aycock, W. C., and Wang, Y. (2004). "Comparison of the new digital flood insurance rate map (DFIRM) with the existing FIRM, Wilson, N.C." *Southeastern Geographer*, 44(2), 159–169.

Bates, P. D., and De Roo, A. P. J. (2000). "A simple raster-based model for flood inundation simulation." *J. Hydrol.*, 236(1–2), 54–77.

De Roo, A. P. J., Van Der Knijff, J., Schmuck, G., and Bates, P. D. (2000). "A simple floodplain inundation model to assist in floodplain management." *New trends in water and environmental engineering for safety and life: Eco-compatible solutions for aquatic environments*, U. Maione, B. Majone-Lehto, and R. Monti, eds., Balkema, Rotterdam, The Netherlands, 1–10.

Dodson, R. J., and Li, X. (1999). "The accuracy and efficiency of GIS-based floodplain determinations." *Proc., 19th ESRI Int. User Conf.*, ESRI, Redlands, Calif.

Feaster, T. D., and Tasker, G. D. (2002). "Techniques for estimating the magnitude and frequency of floods in rural basins of South Carolina, 1999." *Water-Resources Investigations Rep. No. 02-4140*, U.S. Geological Survey, Columbia, S.C.

FEMA. (2001). "Understanding your risk: identifying hazards and estimating losses." Washington, D.C.

FEMA. (2003a). "Digital Q3 flood data availability: States maps." *Q3 availability*, ⟨http://msc.fema.gov/webapp/wcs/stores/servlet/info?storeId=10001&catalogId=10001&langId=-1&content=productQ3Avail&title=Q3%20Availability&parent=productInfo&parentTitle=Product%20Information⟩ (May 29, 2006).

FEMA. (2003b). "Multi-hazard loss estimation methodology: HAZUS-MH." *Technical manual*, Washington, D.C.

FEMA. (2005). "HAZUS annual progress and utilization report for fiscal year 2004." *FEMA, 493*, Washington, D.C.

FEMA. (2006a). "Frequently asked questions: Q3 flood data." *Welcome to flood hazard mapping*, ⟨http://www.fema.gov/plan/prevent/fhm/fq_q3.shtm⟩ (May 29, 2006).

FEMA. (2006b). "Welcome to flood hazard mapping." ⟨http://www.fema.gov/fhm/mm/ahh9.shtm⟩ (May 29, 2006).

FEMA. (2006c). "Policy and claim statistics for flood insurance." *The national flood insurance program*, ⟨http://www.fema.gov/business/nfip/index.shtm⟩ (May 29, 2006).

General Accounting Office. (2004). "Flood map modernization: Program strategy shows promise, but challenges remain." *Rep. to the Chairman, Subcommittee on Housing and Community Opportunity, Committee on Financial Services, House of Representatives Rep. No. GAO-04-417*, U. S. General Accounting Office, Washington, D.C.

Hellweger, F., and Maidment, D. (1997). "AGREE—DEM surface reconditioning system." *GIS hydro 98 water quality*, ⟨http://www.crwr.utexas.edu/gis/gishyd98/quality/agree/agree.htm⟩ (May 29, 2006).

Hodgson, M. E., Jensen, J. R., Schmidt, L., Schill, S., and Davis, B. (2003). "An evaluation of LIDAR- and IFSAR-derived digital elevation models in leaf-on conditions with USGS Level 1 and Level 2 DEMs." *Remote Sens. Environ.*, 84(2), 295–308.

Horritt, M. S., and Bates, P. D. (2002). "Evaluation of 1D and 2D numerical models for predicting river flood inundation." *J. Hydrol.*, 268(1–4), 87–99.

Jensen, J. R. (2005). *Introductory digital image processing*, Pearson Prentice-Hall, Upper Saddle River, N.J.

Jones, J. L., Haluska, T. L., Williamson, A. K., and Erwin, M. L. (1998). "Updating flood maps efficiently—Building on existing hydraulic information and modern elevation data with a GIS." *Open-File Rep. No. 98-200*, U.S. Geological Survey, Water Resource Division, Tacoma, Wash.

Jones, J. L., Haluska, T. L., and Kresch, D. L. (2001). "Updating flood maps efficiently using existing hydraulic models, very-high-accuracy elevation data, and a geographic information system: A pilot study on the Nisqually River, Wash." *Water-Resources Investigations Rep. No. 01-4051*, U.S. Geological Survey, Tacoma, Wash.

Jones, J. L., Fulford, J. M., and Voss, F. D. (2002). "Near real-time simulation and internet-based delivery of forecast-flood inundation maps using two-dimensional hydraulic modeling: A pilot study of the Snoqualmie River, Wash." *Water-Resources Investigations Rep. No. 02-4251*, U.S. Geological Survey, Tacoma, Wash.

Kovacik, C. F., and Winberry, J. J. (1989). *South Carolina: A geography*, University of South Carolina Press, Columbia, S.C.

Kraus, R. A. (1999). "Flood plain determination using ArcView and HEC-RAS." *Proc., 19th ESRI Int. User Conf.*, ESRI, Redlands, Calif.

Krpo, A. (1999). "Next generation of risk management: Floodplain and overland flowpaths modeling linking GIS and hydraulic applications." *Proc., 19th ESRI Int. User Conf.*, ESRI, Redlands, Calif.

Landis, J., and Koch, G. (1977). "The measurement of observer agreement for categorical data." *Biometrics*, 33, 159–174.

Scawthorn, C., et al. (2006a). "HAZUS-MH flood loss estimation methodology. I: Overview and flood hazard characterization." *Nat. Hazards Rev.*, 7, 60–72.

Scawthorn, C., et al. (2006b). "HAZUS-MH flood loss estimation methodology. II: Damage and loss assessment." *Natural Hazards*, 7(2), 72–81.

Schneider, P. J., and Schauer, B. A. (2006). "HAZUS—Its development and its future." *Nat. Hazards Rev.*, 7(2), 40–44.

Shamsi, S. U. (2002). "GIS applications in floodplain management." *Proc., 19th ESRI Int. User Conf.*, ESRI, Redlands, Calif.

U.S. Congress. (2000). "Disaster Mitigation Act." *Public Law 106-390*, 114 Stat. 1552.

U.S. Geological Survey. (2001). "NED Release Notes, Aug. 2001." *Documents*, ⟨http://ned.usgs.gov/Ned/downloads.asp⟩ (May 29, 2006).

U.S. Geological Survey. (2004). “NED Release Notes, June 2004.” *Documents* ⟨http://ned.usgs.gov/Ned/downloads.asp⟩ (May 29, 2006).

Uhlir, P. F. (2003). *Scientific data for decision making toward sustainable development: Senegal River Basin case study*, National Academics Press, Washington, D.C.

United Nations Environment Programme (UNEP). (2002). “Early warning, forecasting, and operational risk monitoring in Asia (Bangladesh, China, and India).” *Project Workshop Proc., GT/1010-00-04, United Nations Environment Programme Division of Early Warning and Assessment (GRID)*, USGS EROS Data Center, Sioux Falls, S.D.

Wang, Y., Colby, J., and Mulcahy, K. (2002). “An efficient method for mapping flood extent in a coastal floodplain by integrating Landsat TM and DEM data.” *Int. J. Remote Sens.*, 23(18), 3681–3696.

Wang, Y., and Zheng, T. (2005). “Comparison of light detection and ranging and National Elevation Dataset digital elevation model on floodplains of North Carolina” *Nat. Hazards Rev.*, 6(1), 34–40.