Riverine Flood Modeling in HAZUS-MH: Overview of the implementation

Subrahmanyam Muthukumar

AUTHORS: Research Associate, Center for GIS, Georgia Institute of Technology. 276 Fifth St. NW, Atlanta, GA 30332-0695
REFERENCE: Proceedings of the 2005 Georgia Water Resources Conference, held April 25-27, 2005, at the University of Georgia. Kathryn J. Hatcher, editor, Institute Ecology, The University of Georgia, Athens, Georgia.

Abstract. This paper presents an overview of how riverine flood hazards may be modeled using the FEMA-developed software application HAZUS-MultiHazard. The paper describes the component-based approach to the application's design, including system architecture and installation. Built-in data accompanying HAZUS and their utilization are also described. The paper traverses the modeling approach from definition of the study region and riverine flood hazards, through the parametric definition of relationships between inventory and hazard-based levels of damage to the actual overlay processes that determine inventory damage counts and levels. The paper concludes with a note on the relationship between the Disaster Mitigation Act of 2000 and FEMA's promotion and utilization of HAZUS-MH.

INTRODUCTION

HAZUS-MH is a nationally applicable software for estimating losses from earthquakes, riverine and coastal floods and hurricanes developed by FEMA with the National Institute of Building Sciences [NIBS], in order to estimate losses based on current scientific and engineering knowledge. Such estimates are essential for public decision-making, development of hazard mitigation plans, emergency preparedness and response and recover efforts. This paper sequences the HAZUS-MH-based modeling of riverine hazards and concomitant damage estimates.

APPLICATION DESIGN AND ARCHITECTURE

HAZUS-MH is built on ESRI's ArcGIS platform for single-user simulations of damage. Distribution packages are free and include data relevant for the entire US. The application has an internal data structure that implements "geodatabases" using SQL Server technology. The data access implementation is innovative in that it uses MSDE [the freebie version of SQL Server 2000], free Data Transformation Services and other ActiveX controls to handle communication, copying, transformation, data creation and linkages between spatial and non-spatial data. Limitations include a 2GB restriction on the active database size and the lack of a user interface for MSDE, both of which may be overcome by using the full version of SQL Server 2000.

HAZUS-MH employs a 3-tier architecture, including a Presentation Layer, an Application Logic Layer and a Data Access Layer, allowing for both independence and sharing of components. Installation includes general and hazard-specific folder structures for executables and data. Component-based architecture and runtime software allow customization and configuration with any relational data repository.

DEFINING THE STUDY REGION

The study region defines the geographic limits of the spatial data, the aggregation level and the hazard used in the estimation. The aggregation process creates filters defined by the hazard type and the study extent and is simply extracted from the datasets accompanying HAZUS-MH. For riverine flood hazards, aggregation occurs at the block level and the study region size is restricted to 4 counties or 90,000 blocks. However, owing to a combination of study region size, terrain resolutions, number of stream reaches and ArcGIS memory leaks, the study region size should be limited to 2 counties. Results from several study regions may be combined for presentation.

Aggregated Data. Data including the general building stock, essential facilities, high potential loss facilities, transportation and utility systems, hazardous materials, agriculture, demographics and vehicles are aggregated to the census block level. General building stock databases are classified by specific occupancy and include square footage, replacement value and building counts, derived from the US Census 2000, Department of Energy Housing Characteristics and Energy Consumption reports, and dun and Bradstreet tabulated data. Quality of the default data varies by area depending on the availability of source data and the effort expended in collection. Users may enhance default data by editing or importing from surveys or detailed specific local inventory components. HAZUS-MH is designed to support different levels of analysis – ***level 1*** using default data with minimal input and model interaction, ***level 2*** for combinations of user-supplied and default data and ***level 3*** for user-supplied flood-specific detailed data.

Flood damage is estimated for specific building types, data for which is not readily available. HAZUS-MH "models" the distribution of the specific structures based on "mapping schemes" described below.

Mapping Schemes. Editable mapping schemes, based on insurance data, expert opinion and inferences from Tax Assessors' database records, generate specific building type distributions for the block level. Since data used by all hazard types is common, mapping schemes generate specific building types by assigning percentages of specific building types to 33 block-specific occupancy categories – specific building types thus generated include flood-specific physical building characteristics that affect damage, such as foundation type and first floor height. Mapping schemes are classified by Pre-FIRM and Post-FIRM structures and may be modified.

DEFINING FLOOD HAZARDS

Defining flood hazards includes sub-steps involving the preparation and utilization of a terrain surface for stream delineation, hydrologic analysis to determine discharge and hydraulic analysis to determine flood depth and extents.

Terrain Surface. HAZUS-MH has a built-in interface that uses the study region extents to download grid-based Digital Elevation Model [DEM] directly from the seamless USGS National Elevation dataset [NED]. Users may supply their own DEMs or use a combination of their DEM and the NED. In order to ensure enough terrain to perform hydrologic analyses, the study region is enlarged by 2 km and combined with a 1km enlarged extent of the intersecting default watersheds. This combined extent is then enlarged by 0.5 km to determine adequate terrain extent requirements. User supplied DEMs must represent bare earth conditions and resolutions must be balanced against file sizes and processing times. Before input into stream delineation, all "sinks" in the DEM must be filled.

Stream Delineation. First, a flow direction grid is created from the DEM based on the 8-direction pour point model following the steepest slope neighbor. Then, a flow accumulation grid is created. Finally, streams are derived from the flow accumulation grid as those grid cells into which more than a threshold number of cells drain into – for a 30m terrain grid, a typical threshold value is about 5000 cells. Small thresholds yield smaller drainage areas with dense stream networks, and may be spurious for the analysis. Raster outputs from this step include flow direction, accumulation grids, lengths and drainage grids per stream segment. Vector outputs in this step include default watersheds, reaches and the stream network. Discrepancies may occur between the synthetic stream channels and channels derived from vector sources or aerial images, mainly because of terrain resolution coarseness. This can be overcome by "burning" in streams by artificially raising the DEM everywhere except in areas of defined stream channels. Based on the complexity, study size area and resolution, developing the synthetic stream network could leak a significant amount of memory and cause system crashes. After the stream network has been generated, specific reaches are selected to define a study case for hydrologic analysis.

Hydrologic analysis. The objective of the hydrologic analysis is to estimate the distribution of water once it lands via precipitation and determine discharge values in streams. Default watersheds are the units of analysis and computations are performed on a reach-by-reach basis. Several methods exist to perform this step including analyzing stream gage data to transform historical peak discharges into flood-frequency curves, or regression functions determining discharge as a function of other variables, or numerical models [HEC-1, SWMM, MIKE11 etc.] to mimic hydrologic processes.

HAZUS-MH implements hydrologic analysis through built-in regression equations to determine discharge-frequency relationships for each reach and include gage and main stream adjustments. Rainfall runoff modeling is not implemented. Regression equation parameters include derived variables [catchment area, mean catchment elevation and slope, and channel length] and default data parameters [temperature, precipitation, soil type, forest cover and snowfall]. Where applicable, regression results are adjusted using the 11,000 stream gage data that accompanies HAZUS-MH. For each gage in the database, flood-frequency data is fitted to a Pearson Type III logarithmic distribution of discharge amounts. Discharge-flood frequency curves are parameterized using mean, standard deviation and skewness. Additionally, HAZUS-MH contains over 16000 reaches in its database that are designated main streams (those with over 100sq. mile drainage thresholds) – discharge values for these reaches are adjusted by interpolating from the corresponding values in the default main stream flood-frequency database. While HAZUS-MH computes only unregulated discharges, adjustments are made to the regression results for existing major regulated streams using built-in regulated flood-frequency curves. No adjustments are made for urban conditions.

The output is a peak discharge table, with discharges computed at each reach's upstream and downstream nodes for return periods of 2, 5, 10, 25, 50, 100 and 500 years.

Hydraulic Analysis. Using the derived discharge values and stream channel morphology, this step computes flood elevations at cross-sections. In general, this step is implemented using Manning's equation or by numerical models [HEC-2, HEC-RAS, SWMM, etc.]. The reach is the unit of analysis and computations are performed on a cross-section basis.

Inputs include discharge, cross-section descriptions [channel slope, cross-section geometry and friction factors for inundated areas], 2-D flow fields, varying Manning's n, bridge geometries, expansion/contraction coefficients and sub-critical/super-critical flow. Outputs include flood elevations at cross-sections, energy head, flood velocity, flood depths and extents. The model is greatly simplified in HAZUS-MH. Inputs include peak discharge, cross-section geometries, 1-D flow field and constant Manning's n for sub-critical flow. Only flood elevations at cross-sections, flood depth and extent grids are generated. The process is iterative. The initial floodplain is estimated by buffering the reaches [buffer distance = $\mathbf{10 * Q^{0.5}}$]. The flow centerline is determined and cross-section lines are placed normal to the flow centerline at intervals of 1000'. Manning's equation is used to determine flood elevations at the cross-sections. A flood surface is determined by interpolating elevations between cross-sections. The DEM is subtracted from the flood surface and the resulting flood conveyance limits are compared with the extents of the depth grid. If necessary, the reach buffers are expanded and the analysis repeated till congruence between conveyance limits and the depth grid is achieved.

Hydraulic analysis may be performed for a single return period, multiple return periods or for a specific discharge – this choice usually dictates the number of reaches that may safely be used in the analysis. Spatial outputs include depth grids by return periods, cross-sections, conveyance boundaries and water elevation points. After the hydraulic analysis, HAZUS-MH allows what-if scenarios including levee-based DEM raising, or regulating flow by modifying the default discharge-frequency curves.

ADJUSTMENT OF MODEL PARAMETERS

Inventory Parameters. Inventory variables consist of the buildings, essential facilities, transportation and utilities, demographics, hazardous materials, agricultural commodities and vehicles aggregated to the block level.

HAZUS-MH replacement value functions for the general building stock are developed from R. S. Means "Square Foot Costs". These functions contain information on the full replacement value as well as the depreciated replacement value. Full replacement value represents the engineering cost to rebuild a structure and is classified by economy, average, custom and luxury structure types.

Depreciated value is the remaining value of a structure based on age and is classified by good, average and poor conditions. The depreciated value reflects the insured value of the property. These definitions/functions are based on individual structures, while HAZUS-MH deals with data aggregated to the block level. The true depreciated value of a block will be a combination of the replacement and depreciation cost models.

For single-family structures, depreciated values are computed at the blockgroup level from default curves of depreciation percent against median age and classified by condition. The overall condition for blockgroup structures is determined by the ratio of blockgroup income to county income. In the case of non-single-family structures, depreciated values are based on construction type, use and observed age. Under default conditions, the observed age is assumed similar to residential uses. Depreciation parameters encoded within HAZUS-MH may be modified by the user.

Default mapping schemes that convert specific occupancy types into building type with foundation types and first floor heights may be modified by the user.

Default agricultural data are provided by National Resources Inventory [NRI] and National Agricultural Statistical Survey [NASS] and compiled into sub-county polygons formed by the intersection of 8-digit HUCs with county boundaries. HAZUS-MH uses the available land use/land cover data and includes default data on crop types, quantities, yields, unit prices and harvest costs after removing non-agricultural areas. All crop types and associated attributes may be modified by the user.

The number and type of vehicles are estimated from square footage to vehicle ownership ratios using methods adopted by most MPOs for their transportation planning needs. Vehicles are classified by car, light truck or heavy truck typologies and by age [new/old] and estimated at the block level for day-time and night-time periods.

Damage Parameters. Damage to inventory categories is based on built-in depth-damage curves. These depth-damage curves relate damage as percent of replacement cost against effective flood depths – effective flood depths are quantified as the height of flood waters above the first floor. Every inventory item is associated with a default depth-damage curve. For the general building stock, each of the 33 specific occupancy classes and their variations by foundation type and building height have associated curves. For bridges, utilities and vehicles, depth-damage curves are derived from historic data and expert opinion. Agricultural depth-damage curves are derived from USACE district curves and other models such as USACE IWR, USACE AGDAM, etc. Agriculture damage curves are associated with additional parameters including flood depth, duration of inundation, flood date relative to crop cycle and crop type. All depth-damage curve values are encoded as tables and may be modified by the user.

Restoration Parameters. As in the other cases, HAZUS-MH has built-in restoration parameters that are based on occupancy restoration timelines. For some inventory items, these curves indicate an assessment of the functionality. All restoration curves have values for the maximum restoration time for 100% operations. Restoration parameters are tabulated and may be modified by the user, but without in-depth domain knowledge, it is safer to use defaults.

Analysis Parameters. HAZUS-MH has an analytical parameter modification interface to alter estimations of debris, shelter requirements, direct and indirect economic losses. Casualty estimation has been deferred.

Estimated weights of debris generated are limited to building-related components [building finishes, structural elements and foundation materials] and does not include vegetation, sediment or building contents. Default debris parameters are listed by specific occupancy classified by foundation type and tabulated for specific flood depth intervals.

Default shelter parameters are based on total population displaced owing to evacuation/flooded roads. Evacuation factors include access restriction heights and additional public safety evacuation buffers. Displaced populations may be weighted by demographic factors including income, age, ethnicity and home ownership, and by utility outages as percent impacted households.

Direct economic loss parameters have been generated only for occupancies with inventory considerations and are based on gross sales data for 2002. Direct economic loss parameters deal with losses caused primarily by business interruption and take into account restoration times for business interruption interval estimation.

Estimates of indirect economic losses are based on simplified models of a synthetic economy classified by type and size. Employment numbers are based on the Bureau of Economic Analysis 2002 figures for counties, and include unemployment rate, level of outside aid/insurance, interest rates on loans and reconstruction costs.

All analysis parameters may be modified by the user. Additionally, all estimated losses may be modified based on flood warning studies conducted by the USACE in the 1960s. Flood warnings include default curves relating damage reduction to flood forecasts. Editable warning parameters for damage reduction include flood warning lead time, warning dissemination and response rates.

OVERLAY ANALYSIS FOR LOSS ESTIMATION

Since most data are aggregated to the census block level, damage is estimated at the census block level and then translated into estimates of losses using the damage, restoration and analytical parameters described above. This approach is valid for large areas – level 2 and level 3 users may include point-specific data; essential facilities, bridges and utilities are evaluated by their specific locations.

Flood damage is conducted through an area-weighted estimation process overlaying block and site specific data with the flood depth grid. The process assumes that the building stock inventory is distributed at uniform density within the block. The number of grid cells corresponding to a given inundation depth is divided by the total number of grid cells within the block to derive the "damage area-weights." These weights are used to distribute damage to specific occupancy/foundation type for that particular flood depth. In other words, the weight is multiplied by the number of buildings [in the block] of a particular specific occupancy/foundation type combination in order to estimate the number of buildings of that combination subject to a particular inundation level. The damage, restoration and analysis parameters are applied to the damaged building inventory from in the overlay process.

All the inventory, hazard and estimated damage for all categories may be viewed in ArcGIS-based map form or as formatted report using the built-in reporting module.

CONCLUSION

HAZUS-MH results vary by the quality of input data and the degree of user-interaction with the flood model, and caution should be exercised in evaluating damage and loss estimates.

The Disaster Mitigation Act of 2000 [DMA 2000] requires state and local jurisdictions to prepare hazard maps and disaster mitigation plans. The consequence for counties of failure to develop an infrastructure mitigation plan is the chance of a reduced federal share of damage assistance from 75%to 25% if the damaged facility has been damaged on more than 1 occasion in the preceding 10-year periods by the same type of event. In an effort to promote HAZUS-MH, FEMA has advised jurisdictions that plans using scenario-based estimates generated by a HAZUS-MH level I analysis will be accepted as is. The free application would make it worthwhile for resource-poor counties to meet DMA 2000 requirements.

While this paper describes riverine modeling only, HAZUS-MH models coastal flooding hazards also. In general, its free availability, concomitant data and ease of use make it a worthwhile addition to local government software.

SELECTED REFERENCES

Maidment, David R., 2002. *Arc Hydro: GIS for Water Resources.* ESRI Press, Redlands, CA.

.___________, 2003. *Multi-Hazard Loss Estimation Methodology – Flood Model: HAZUS MH Technical Manual.* Department of Homeland Security, FEMA Mitigation Division, Washington, D.C.

DMA 2000. *Disaster Mitigation Act 2000.* URL -- http://www.fema.gov/fima/dma2k.shtm