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ORIGINAL PAPER

# Adaptation planning for floods: a review of available tools

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**Abstract** Communities have competing priorities for limited financial resources. Identifying a capable and affordable tool that can be used in flood adaptation planning will assist in determining strategic investments and enhancing public communication. A state-of-the-art review was conducted of commonly available flood modeling and impact assessment tools that could be utilized for climate adaptation planning by municipalities. Assessment criteria such as flood modeling capabilities, geographic information system integration, damage assessment functions and ease of use were used. Although there are many tools available, based on the criteria used in assessing these models, the US Federal Emergency Management Agency's Hazus-MH tool appears to hold the most promise in being repurposed for adaptation planning.

**Keywords** Flood · Adaptation · Planning · Communities · Municipalities · Tools · Models · Geographic information systems · GIS · Climate change · Extreme weather events

## 1 Introduction

With the 1990 publication of the first assessment report by the United Nations' Intergovernmental Panel on Climate Change (IPCC), there has been increasing focus on climate change and its impacts. Of the many hazards associated with climate change, flooding presents some of the most frequent and severe consequences. Worldwide in the period from 1900 to 2013, flooding was the most frequently occurring natural disaster impacting more people than any other natural disasters. For the same period, flooding in the USA was second only to storms in impacts to people and cost of damage (EM-DAT 2013).

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Exacerbating this situation is that flooding can occur at any time of year and in any part of the USA (Mileti 1999).

It is becoming increasingly apparent that climate change mitigation efforts, such as reduction of greenhouse gases, will not be sufficient to stop or reverse its increasing impact on the environment (IPCC 2007). Consequently, adaptation is becoming a more prominent risk reduction strategy, making the development of effective tools to assist in adaptation planning a prudent course of action. Examples of adaptation strategies include strengthening existing infrastructure or scheduling more frequent maintenance to alleviate increased wear and tear caused by extreme weather, such as excessive heat or flooding.

Tools that model flood inundation and perform damage assessment have historically been directed at planning for disaster response or developing flood insurance rate maps (Mudaliar 2011; Flo-2D Software 2012; FEMA 2008, 2012b). This paper presents a review of currently available flood damage assessment tools and their ability to be repurposed for adaptation planning.

## 2 Model selection criteria

The review evaluated currently available flood modeling tools with consideration of their ability to perform flood modeling and damage assessment estimation. Additional consideration was given to the ease with which a municipality or other organization might both obtain and utilize such tools (Chau 1995). Criteria employed for evaluation included the following:

- extent and resolution of area modeled
- ability to perform flood hazard analysis at least at a two-dimensional (2D) level
- presence of infrastructure damage assessment and loss estimation function
- ability to perform or support spatial data viewing capabilities, such as geographic information systems (GIS)
- affordability
- technical skills required for use
- training required/available
- technical support
- hardware requirements

The latter four factors are considered "organizational criteria" in the ensuing discussion and represent those that are not critical for pure damage analysis, but may become limiting in a municipality's ability to utilize the tool for adaptation planning. We next discuss each of these criteria.

### 2.1 Extent and resolution of area modeled

Tools capable of covering a large area with sufficient stream detail are critical to ensure sufficient flood extent and impact definition. A favorable selection criterion is a tool that can perform estimates over a wide range of areas with the potential for high resolution.

### 2.2 Ability to perform flood hazard analysis

Flood hazard analysis includes the ability to model parameters defining a flood event with an ability to view or evaluate the potential for flooding, its extent (inundation area) and flow characteristics (Scawthorn et al. 2006). An acceptable tool should be capable of performing, at a minimum, 2D flood analysis to show both the depth and extent of a flood event.

### 2.3 Presence of damage estimation function[1]

Once the flood boundaries are defined, the capability to estimate damage is essential. Damage estimation can be performed as a core function of the software or externally via export to another product. Tools that explicitly perform damage estimation, particularly those that assess damage categories (e.g., damage by building type and inundation level), are considered desirable under this criterion.

### 2.4 Ability to perform or support spatial data viewing capabilities

Research has shown that public forums with rich media use improve message clarity (Baker et al. 2005). Spatial data viewing, utilizing GIS technology, provides for a means for effective communication. Such visualization can display specific areas of flood impact and resulting damage.

### 2.5 Affordability

Price may be a limiting factor in software selection. A favorable attribute for this criterion is a tool (inclusive of any ancillary software required) whose acquisition cost is affordable. With municipalities in mind as potential users, a purchase cost of $10,000 is considered a reasonable affordability threshold.

### 2.6 Organizational criteria

Tools that are easy to use, sufficiently detailed to produce meaningful results and can be manipulated by someone familiar with common business software are preferred, given the wide variety of personnel who may use the product. The criterion of short-duration, domestically available training minimizes personnel time away from work and ensures no unforeseen embedded cost in the product. Since problems often arise in software use, having an accessible technical support base, in any form, works to minimize disruptions. Finally, software that runs on commonly available platforms (e.g., the Intel Core 2 processor family or their AMD equivalents) allows the system to run without any special hardware or additional expense.

### 2.7 Tool evaluation

The following presents a review of commercially available flood tools and an assessment of their ability to meet the aforementioned criteria considered desirable in supporting adaptation planning.

[1] Damage includes all consequences associated with a flood event such as loss of life, direct physical loss, and indirect and direct financial impact.

### 2.8 Flo-2D

Flo-2D is a software program capable of performing one-dimensional (1D) and 2D hydrodynamic analysis (simulated channel flow, unconfined overland flow and street flow over complex topography). The 2D flood modeling is based on user input and various topographic features. Flo-2D does not have a size limit to the area modeled and can model grid elements as small as 100 square feet (Flo-2D 2012). Flood damage assessment may be performed using depth–damage functionality inherent to the program, although it requires the user to develop cost tables and the polygon association for export to a GIS program (O'Brien 2009). Damage estimation is performed using GIS data comparison functions to estimate the amount of damage within a given polygon based on flood extent/depth. These damage estimates are linked with the polygons' associated cost data and summed for total cost. The primary shortcoming of this approach is that the definition of data to include in cost estimates is at the discretion of the user with no standard for impact analysis. The program requires no adjunct software for flood modeling and uses extensions included with the software to allow GIS export and mapping functionality (Flo-2D 2012). The program is priced at $3,495 for a single-user license. Additional capabilities for hydrodynamic modeling of riverine flooding exist through RiverFlo-2D, which can be purchased for $3,950. The developer offers online training at a cost ranging from $50 to $200 depending on the course taken and whether technical support is through telephone or email communication.

### 2.9 TUFLOW

TUFLOW flood modeling software may be used as a stand-alone application or can be integrated into other flood model software. The software consists of two numerical engines: (1) TUFLOW which does 1D/2D modeling and (2) TUFLOW FV which does three-dimensional (3D) modeling. To use TUFLOW, a GIS program, text editor, spreadsheet program and a 3D surface modeling program, such as surface modeling software (SMS) or waterRIDE, are required (Aquaveo 2013; WorleyParsons 2013). As a stand-alone application, TUFLOW uses GIS software to create data files such as 2D grid locations, topography and digital terrain models, as well as viewing model output. If the GIS cannot perform the function, separate 3D SMS is used to create the digital terrain models. A text editor is used to create items such as simulation control files, while the spreadsheet software is used for boundary time-series data (BMT Group Ltd 2012). Pricing for TUFLOW begins at $6,000 for a single license (BMT Group Ltd 2012). Data inputs for damage assessment require the user to develop depth–damage relationships and link these through a tool such as GIS with the flood data from TUFLOW. Software training is available at a cost of roughly $500 per class (BMT Group Ltd 2012). TUFLOW offers technical support both through a wiki site as well as through contracted services.

### 2.10 Surface modeling software (SMS)

SMS (Aquaveo 2013) is a suite of software packages, comprised of SMS-TUFLOW, SMS-SRH2D and SMS-ADCIRC, which is available for a variety of applications. SMS-TUFLOW uses a graphical user interface (GUI) with TUFLOW as the engine for modeling complex surface flows. SMS-SRH2D is a version with higher capability for modeling stream flows and which incorporates greater ability to include in-stream structures and water returns (Aquaveo 2011b). SMS-ADCIRC is used for modeling flows in and around oceans. Of these options, SMS-TUFLOW is the most relevant product relative to the review criteria (Aquaveo 2011a). The data from SMS-TUFLOW can be used by the program itself or output to GIS software. SMS-TUFLOW models hydraulic data but does not perform damage assessment for flood scenarios. An advantage of the software is its ability to model very large areas for flooding or inundation (Ballard 2012). SMS-TUFLOW costs approximately $9,000 for a single-user license (Aquaveo 2011c). The developer offers training at a cost of approximately $1,400 for a 1-week course on 1D/2D modeling using the product.

### 2.11 XP-SWMM

XP-SWMM can be used to model a variety of hydraulic scenarios, including floodplain management (XP Solutions Inc. 2011). The software can perform 1D and 2D analyses, but requires an add-on, XP2D, to perform flood inundation analysis. As with SMS-TUFLOW, the XP2D module uses the TUFLOW engine. Although a GIS-like interface is available with the product, the data can also be integrated with external GIS programs for different modeling area sizes (XP Solutions Inc. 2012a). Software training is available beginning at $1,300 for a 2 days class or $350 for an online training event. A single-user license, which includes XP-SWMM and up to 10,000 cells of XP-2D, is available for $3,200 (XP Solutions Inc. 2012b). The tool is priced based on number of cells modeled. If a finer resolution cell is used (e.g., 100 feet by 100 feet), the area modeled will be smaller than a larger cell size (Bouchot 2012). Given this condition, the user must have some idea as to what resolution will be required as well as the size of area to be modeled. Failing to appropriately size the modeling space may lead to results with insufficient resolution or unnecessary expenditure. As with SMS, the software has no inherent damage assessment function and would rely on integration with a secondary program to perform damage analysis (XP Solutions Inc. 2012a).

### 2.12 MIKE Flood

MIKE Flood also performs 1D and 2D flood analyses. The program utilizes aspects of three software packages: (1) MIKE 11 for river modeling, (2) MIKE URBAN for urban flows and (3) MIKE 21 for 2D flow modeling (DHI 2011). The program has a toolbox for flood damage assessment that integrates with ArcGIS, which can calculate damage per unit area in any specified currency. However, the user must supply specific depth–damage estimates for various land uses (Landrein 2011). Training is available for both urban and river applications of MIKE Flood, with each course costing $1,110 (DHI 2012). MIKE Flood license fees begin at $18,500 (Johnston 2012).

### 2.13 waterRIDE

waterRIDE offers a GIS interface as well as capability to export to other GIS platforms. It performs both 1D and 2D flood hazard analyses using TUFLOW as well as having the ability to use multiple other models (e.g., HEC-RAS, MIKE11, MIKE21, XP-SWMM). The software can use fine-scale digital terrain models for the extent and resolution of area modeled (Worley-Parsons 2012). waterRIDE can also perform damage assessments by using depth–damage relationships generated from regional experience, such as insurance claims and damage research. The program extrapolates the flood model depths and extents to estimate the amount of damage to a given structure type (e.g., concrete slab construction). Infrastructure components can be modeled if the necessary data are included in the depth–damage development (Lam 2012). As with MIKE Flood, waterRIDE offers a tool with integrated flood modeling and damage estimation. waterRIDE licensing fees begin at $15,000 (Copenhaver 2012).

### 2.14 ISIS

ISIS is a group of flood modeling tools comprised of ISIS Professional, ISIS 2D and the ISIS-FAST program. ISIS Professional performs 1D modeling of flows found in settings such as open channels or estuaries. The ISIS 2D product, as the name suggests, performs 2D modeling of water flow. It can be used for water management plans and flood modeling. ISIS-FAST is designed to rapidly assess a variety of flooding scenarios, including tidal surge and levy breaching. Each of these products has its own GIS interface, or output can be directed to other GIS applications. ISIS also offers a variety of add-ons to perform functions such as increasing the number of nodes for flooding, mapping output from the tools and linking ISIS with TUFLOW. ISIS is supported by both a free, online user community and a fee-based support system (Halcrow Group 2012). Property loss estimates and infrastructure damage are based on depth–damage relationships. As of December 2011, ISIS contains only depth–damage information for the UK, so users in other locations would be required to develop data for their native area (Adams 2011). Although there is a no cost-limited version of ISIS available, the full-featured program begins with a base price of $7,680 per year for a single-user license. Additionally, there is an annual support and maintenance fee starting at $1,350. Classroom training is available beginning at $400; however, course offerings are hosted in Great Britain (Halcrow Group 2012).

### 2.15 HEC-RAS

HEC-RAS is the United States Army Corps of Engineers (USACE) Hydrologic Engineering Centers' River Analysis System. It is free software that performs 1D hydrologic modeling for natural and constructed channels. No damage assessment function is provided, but flood data can be output to ArcGIS through the use of an ArcGIS shapefile or HEC-GeoRAS. Although HEC-RAS contains its own viewer for flood visualization, the HEC-GeoRAS program provides a more robust interface with ArcGIS (USACE 2012b), providing a tool kit for using ArcGIS to create input files for HEC-RAS analysis as well as to use HEC-RAS output for presentation in ArcGIS (USACE 2009). Neither through HEC-RAS itself nor through the HEC-GeoRAS tool does the program provide damage analysis, however. For non-governmental users, training and support for the tool is solely the responsibility of the user. Should support in using the software be required, USACE recommends performing an online search for vendors offering this service (USACE 2012c).

### 2.16 HEC-FIA

Also available from USACE is the Hydrologic Engineering Center's Flood Impact Analysis (HEC-FIA) tool. HEC-FIA differs from HEC-RAS in that it utilizes data relative to structures, crops and people to perform flood damage analysis. Flood data are provided to the system through a watershed tool, which allows the user to either create a watershed and associated attributes or import them from other HEC software (USACE 2012a). Once created, an impact area is identified by the user. HEC-FIA allows the user to either develop and import their own data for structural inventories (e.g., buildings, vehicles) or import the structure data from FEMA's Hazus database for buildings. Once imported, HEC-FIA users can make both global and specific modifications to certain structural attributes such as foundation height, occupancy, structure value and content parameters (USACE 2012a). Similarly, HEC-FIA allows agricultural data to be imported from Hazus with modifications for crop loss functions (USACE 2012a). Of note is the loss methodology applied by HEC-FIA to structures and agriculture. For structure damage, HEC-FIA looks only at flood height to predict damage to structures. Flood depth, time of year flooding occurs, duration of inundation and drying time are used in determining agricultural damage. Additionally, the loss of life function in HEC-FIA is rather detailed. The program uses a "warning diffusion" algorithm to predict how rapidly the public is made aware of a problem based on the warning system used. Coupled with this is a mobilization function to determine how quickly personnel can evacuate to a safe zone (USACE 2012a). These loss functions allow for very specific and detailed analysis of flood impacts within an area. The software runs on commonly available systems, and training courses are offered by USACE at a cost of $2,350 per course (USACE 2012a). Software technical support is up to the user since HEC does not list vendors for support nor is it offered from USACE (USACE 2012a). However, training workshops are sometimes offered by professional associations such as the American Society of Civil Engineers.

### 2.17 ArcGIS

ESRI's ArcGIS can perform hydrologic analysis through its Spatial Analyst extension, which includes a 2D advection flood model. Hydrogeological data are used to generate groundwater flow fields, which then may be used to map at-risk parcels (ESRI Inc. 2012c). ArcGIS does not possess inherent damage estimation functionality and would require the user to develop and import this information for impacted areas. Additionally, the user would be required to develop damage relationships, such as depth–damage curves, to determine impact in a given area. The software has a GUI and runs on commonly available PC hardware (ESRI Inc. 2012a). The basic ArcGIS program begins at $1,500 with the Spatial Analyst extension costing an additional $2,500 (ESRI Inc. 2012b). Training is available from ESRI for $1,000 for a 2-day course on hydrologic analysis using ArcGIS (ESRI Inc. 2012e).

### 2.18 Hazus-MH

Developed by the Federal Emergency Management Agency (FEMA), Hazus-MH tool performs flood hazard and flood damage analysis along with damage analysis for hurricanes and earthquakes (FEMA 2012a). Although Hazus-MH itself is free, it does require ESRI's ArcGIS and Spatial Analyst software which, as previously mentioned, costs $1,500 and $2,500, respectively (ESRI Inc. 2012b). Packaged within the Hazus-MH software is a 2D flood modeling tool, an inventory of land use and estimated values by US census tract, data on critical infrastructure such as bridges, depth–damage curves for various occupancy and building types and algorithms to predict both direct and indirect losses from flooding (FEMA 2009). Hazus-MH also has capabilities to utilize output from more robust flood models such as HEC-RAS for use in the damage analysis. Training is available online through ESRI as well as offered to government users through FEMA's Emergency

Management Institute (EMI). Tuition for Hazus training at EMI is free, but travel costs are not covered except for government personnel (EMI 2013). Approximately ten classes are offered online through ESRI for Hazus-MH at roughly $30 per course (ESRI Inc. 2012d). Technical support is available through the Hazus-MH webpage and the FEMA Map Information Exchange toll-free line (FEMA 2012a).

### 2.19 Summary of tool analysis

A summary of the characteristics of the aforementioned tools relative to the evaluation criteria for flood adaptation planning is provided in Table 1. All tools surveyed possessed similar capabilities for modeling flood extent and depth as well as hardware required to run the programs. The assessment criterion that provided the greatest differentiation between tools was the presence of an inherent damage assessment function with only four of the tools evaluated possessing this capability. Beyond having a damage assessment capability built-in, the remaining categories provided only modest differentiation between the tools.

The four tools evaluated that had damage assessment capabilities included HEC-FIA, waterRIDE, MIKE Flood and Hazus-MH. MIKE Flood and waterRIDE were removed from further consideration due to pricing above the set $10,000 limit of the affordability criterion. HEC-FIA was further excluded due to an absence of technical support and the need for robust technical skills required for use. Of all the tools evaluated, only FEMA's Hazus-MH fulfilled all assessment criteria.

### 2.20 Findings and implications

A variety of flood modeling and impact assessment tools were evaluated for potential repurposing in flood adaptation planning. Evaluation criteria considered both technical abilities to perform flood modeling and damage assessment analysis as well as additional factors that might limit a municipality's ability to actually utilize the tool (e.g., training, software and hardware requirements).

While a number of products are available that could be used to model floods and corresponding impacts, Hazus-MH was identified as the best option for flood and damage estimation for municipalities. Hazus-MH is able to model, within its resident capabilities, flood scenarios in terms of their area and extent, damage estimation and provides GIS mapping of flood inundation areas and damaged areas to support visual communication of results. Moreover, the software is affordable, both in terms of acquisition cost and training and technical support.

Hazus-MH provides the user with a number of useful inherent functionalities and inventories. Hazus-MH provides the user the option of modeling flooding using built-in return periods for flood events (e.g., 100, 250, 500 years) using digital elevation models and national data as well as the capability to read output from hydrodynamic models such as HEC-RAS. The depth–damage functions supplied with Hazus-MH come from a variety of reputable sources such as USACE and the US Federal Insurance Administration (Scawthorn et al. 2006). Coupled with this are preloaded inventories of building types, economic data, lifeline utility data and agricultural data from sources such as the US Census Bureau, Dun and Bradstreet and the US Department of Agriculture. In addition to a depth–damage function and an inventory of businesses and buildings for a given census area, Hazus-MH also comes with the ability to perform direct and indirect economic loss estimates as well as displaced person estimates for a flood event (FEMA 2009).

**Table 1** Assessment of tools relative to evaluation criteria

| | Extent and resolution of area modeled | Ability to perform flood hazard analysis at least at a 2D level | Presence of infrastructure damage assessment and loss estimation function | Ability to perform/ support spatial data viewing (e.g., GIS) | Affordability | Technical skills required for use | Training required/ available | Technical support | Hardware requirements |
|---|---|---|---|---|---|---|---|---|---|
| FLO-2D | • | • | – | • | • | • | • | • | • |
| TUFLOW | • | • | – | – | • | • | • | • | • |
| SMS | • | • | – | • | • | • | • | • | • |
| XP-SWMM | • | • | – | • | • | • | • | • | • |
| MIKE Flood | • | • | • | • | – | • | • | • | • |
| waterRIDE | • | • | • | • | – | • | • | • | • |
| ISIS | • | • | – | • | • | • | – | • | • |
| HEC-RAS | • | – | – | – | • | • | • | • | • |
| HEC-FIA | • | • | • | • | • | – | • | – | • |
| ArcGIS | • | • | – | • | • | • | • | • | • |
| Hazus-MH | • | • | • | • | • | • | • | • | • |

In summary, Hazus-MH comes with multiple options for modeling flooding and includes valuable data for a community to utilize in flood planning and damage assessments. Additional research is required to determine effective incorporation of Hazus into adaptation planning.

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