LA-UR- 07-0354

Approved for public release; distribution is unlimited.

Title: GIS-Based Prediction of Hurricane Flood Inundation

Author(s): D. Judi, A. Kalyanapu, S. Burian, S. Linger, A. Berscheid, and T. McPherson

Intended for: EWRI Environmental & Water Resources Congress 2007

Los Alamos
NATIONAL LABORATORY
EST 1943

GIS-Based Prediction of Hurricane Flood Inundation

D. Judi[1,2], A. Kalyanapu[1], S. Burian[1], S. Linger[2], A. Berscheid[2], and T. McPherson[2]

[1] Department of Civil and Environmental Engineering, University of Utah, 122 S. Central Campus Drive, Suite 104, Salt Lake City, UT 84112; Phone: (801) 585-5721; Fax: (801) 585-5477; E-mail: burian@eng.utah.edu
[2] Los Alamos National Laboratory, Los Alamos NM 87545

Abstract

A simulation environment is being developed for the prediction and analysis of the inundation consequences for infrastructure systems from extreme flood events. This decision support architecture includes a GIS-based environment for model input development, simulation integration tools for meteorological, hydrologic, and infrastructure system models and damage assessment tools for infrastructure systems. The GIS-based environment processes digital elevation models (30-m from the USGS), land use/cover (30-m NLCD), stream networks from the National Hydrography Dataset (NHD) and soils data from the NRCS (STATSGO) to create stream network, subbasins, and cross-section shapefiles for drainage basins selected for analysis. Rainfall predictions are made by a numerical weather model and ingested in gridded format into the simulation environment. Runoff hydrographs are estimated using Green-Ampt infiltration excess runoff prediction and a 1D diffusive wave overland flow routing approach. The hydrographs are fed into the stream network and integrated in a dynamic wave routing module using the EPA's Storm Water Management Model (SWMM) to predict flood depth. The flood depths are then transformed into inundation maps and exported for damage assessment. Hydrologic\hydraulic results are presented for Tropical Storm Allison.

Introduction

Flood inundation prediction is necessary to plan for disasters (e.g., hurricane flooding, flash flood warning) and design effective mitigation strategies and structures. Numerous approaches and mathematical models have been developed to predict flood inundation. Several have incorporated capability to process data in a geographic information system (GIS) and visualize output. Fewer yet have provided a comprehensive simulation from hydrograph, flood depth, and inundation prediction to damage and infrastructure service consequence assessment in a seamless decision support system. The unique feature of the modeling system described in this paper is not only its comprehensive coverage and full implementation in ArcGIS, but also the integration of the flood flow simulation capabilities into an overall event simulation framework to investigate impacts from flood events on different infrastructure systems.

Methodology

The objective of this research is to develop the capability to rapidly simulate flooding from extreme events of national importance (e.g., hurricanes) and assess damage to and impacts on operation of infrastructure system operation (including interdependency analysis). This paper presents progress to date on the integration of extreme flood event prediction with infrastructure analysis models. The case study presented is the flood inundation simulation for inland flooding resulting from extreme rainfall events.

Inland flooding prediction includes hydrologic\hydraulic computations and mapping of flood inundation extent and depth in a seamless process. Rainfall predictions are obtained from a numerical weather model and ingested in gridded format into the simulation environment. Hydrographs are then generated and routed downstream using a dynamic wave simulation in the EPA's Storm Water Management Model (SWMM). The resulting hydraulic grade lines (HGL) are transformed into a water surface raster and, subsequently, the flood depth and extent is determined. The resulting depth contours are then used in estimating damage to critical infrastructure.

Rainfall

Gridded rainfall shapefiles obtained from any simulated rainfall models are used as an input parameter in determining the rainfall hyetograph. For each time step, the corresponding gridded rainfall is intersected with sub-basin polygons. An incremental rainfall amount is determined for each sub-basin at the time step using an area-weighted average method. Upon completion of all time steps, all incremental rainfall values calculated for each basin are written to a text file for use in the hydrologic model.

Hydrology

The hyetographs are used to determine the runoff hydrographs from each sub-basin. The model has two methods for determining the runoff, a lumped parameter model and a physically based distributed hydrologic model.

Snyder's unit hydrograph is a lumped parameter model based completely on the geometric properties of the sub-watershed. This method was implemented first in the model because of its simplicity and also its ability for rapid analysis. This method relies only on the calibration of two parameters, C_p and C_t, which typically range from 0.5 to 0.7 and 1.8 to 2.2, respectively.

A more physically based approach to determining rainfall runoff was developed using a raster based distributed hydrologic modeling approach to estimate overland flow, which includes using Green-Ampt infiltration to determine excess rainfall and 1D diffusive wave method for overland flow routing (Kalyanapu 2006). This model was developed for efficient application with limited data requirements (soils, land use, and topography) and very little calibration.

Hydraulics

The hydrographs are passed into the hydraulic model as an input parameter. Additionally, channel cross-sections are needed for one-dimensional hydraulic simulation of flooding. Channel cross-sections, in SWMM format, may either be surveyed data or generated using an automated extraction method using digital elevation data (Kalyanapu et al. 2007). The input hydrographs are routed to the closest downstream junction and time adjusted based on distance and an assumed velocity. Using the SWMM file containing the cross-sections, the hydrographs are appended as inflows at the corresponding junction. Once the SWMM input file is complete, the SWMM .dll file is called and the generated input file is passed in as a parameter and a dynamic wave simulation is run in the background of a GIS for the user specified duration. Upon completion of the simulation, the HGL for each cross section is exported and stored for use in flood mapping.

Flood Mapping in GIS

The objective of the flood inundation mapping component is to provide a visualization of the flood depth and extent and ultimately create a depth contour shapefile representing the depth and extent of flooded areas. The contours will be used as an input for damage estimation due to flooding. This process is broken down into three steps: (1) flood boundary delineation, (2) creation of a raster representing the water surface, and (3) computation of the flood depth contours.

The flood boundary is delineated by using the HGL elevations and the ground elevations. The boundary vertices are located by comparing the two elevations at each cross-section. This is done by starting at the channel centerline and systematically moving in an outward direction along the cross-section in both directions. The point at which the HGL is less than the ground surface elevation is a boundary point.

The raster representing the water surface is created using the computed HGL elevations and the boundary polygon. A TIN is first interpolated using the HGL values at each cross-section point as source values and the boundary polygon as a soft clip boundary. This permits the surface to be created only within the limits of the boundary, thus eliminating disconnected flooded areas. The TIN is then converted into raster format for further calculations.

The third and final step is to calculate the flood depth contours. This is done by first subtracting the ground surface elevation raster from the HGL raster surface. The resulting raster represents the flood depths. In order to remove negative depths and classify the depths according to a standard scale used by the damage estimation function, the depth raster is reclassified. The standardized depth scale is shown, in feet, in Table 1 below.

Table 1- Reclassified Code Values

Code	Values (ft)	Code	Values (ft)
0	<= 0	15	14-15
1	0-1	16	15-16
2	1-2	17	16-17
3	2-3	18	17-18
4	3-4	19	18-19
5	4-5	20	19-20
6	5-6	21	20-21
7	6-7	22	21-22
8	7-8	23	22-23
9	8-9	24	23-24
10	9-10	25	24-25
11	10-11	26	25-26
12	11-12	27	26-27
13	12-13	28	>27
14	13-14		

Finally, the reclassified raster is converted into a depth contour shapefile and ready to be used as input into the damage estimation module.

Damage Assessment

Damage estimation is done by utilizing depth-damage functions that have been developed for use in FEMA's HAZUS-MH (FEMA 2006). Currently, the assessment is only done for "lifeline" utilities, defined as those that provide the United States with communications, water, power, mobility and other necessities for both continuity of governance and economic health (FEMA 2006). The depth-damage functions represent the percent damage to a facility based on a depth of water. In addition, the depth-damage functions indicate the depth of water at which the facility is no longer functional.

Using the flood depth contours generated from an inland flooding, an assessment of damage to and impacts on operation of infrastructure systems may be completed. The depth contours are joined with the damage functions to produce two new shapefiles. The shapefiles represent estimated percent damage for each type of utility and whether or not each utility is functional, respectively.

Case Study

The Greens Bayou watershed is located in Harris County, northeast of the Houston, Texas downtown area. The watershed is approximately 196 mi² and consists of a variety of land use/cover types and soil layers. The majority of the land use/cover is urban, consisting of residential, commercial, industrial, transportation, and open space. The elevation in the watershed varies from 425 feet above mean sea level, to just 25 feet (Waclaw, 2003). Figure 1 shows the Greens Bayou watershed in the Houston metro area.

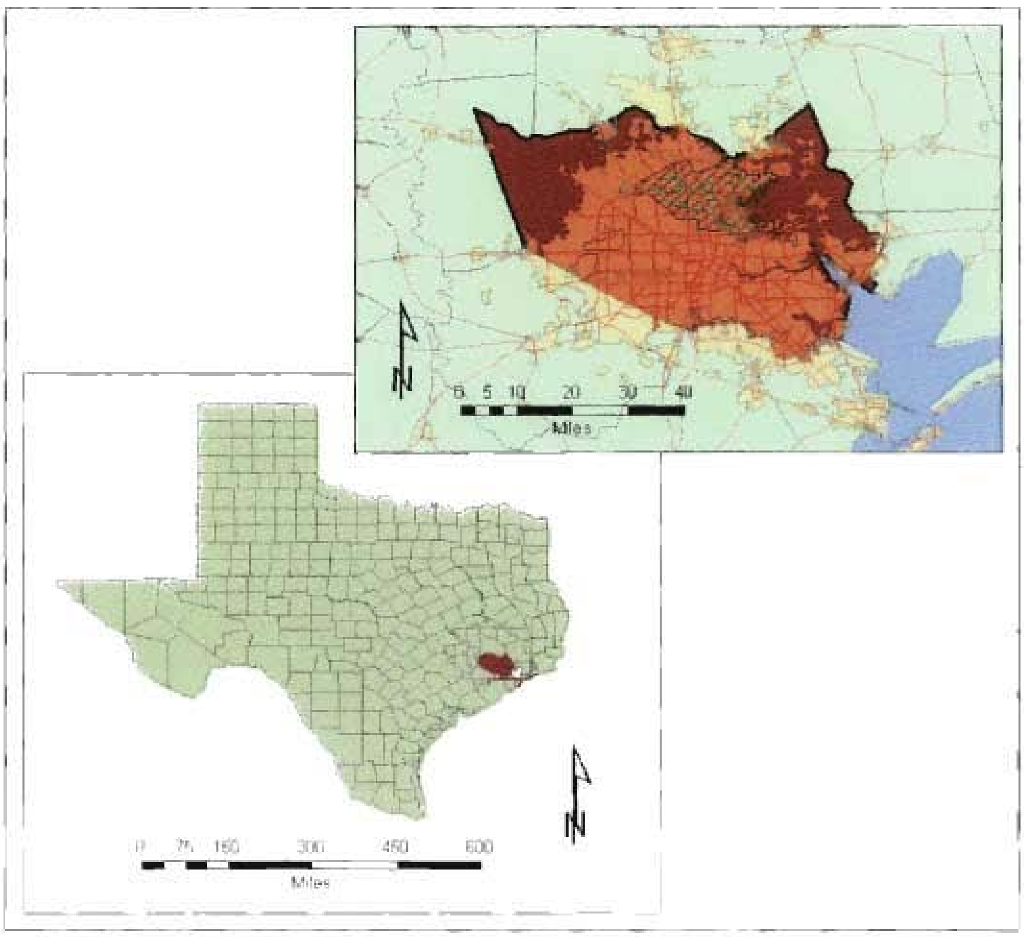

Figure 1- Greens Bayou watershed (stripes, upper right) Located in Houston, Texas

Tropical Storm Allison was a major rainfall event during the summer of 2001, affecting the entire Houston metro area. The Greens Bayou watershed was among areas receiving the greatest amounts of precipitation with measurements as high as 34 inches over the duration of the event. The tropical storm occurred in three distinct rainfall events. The third event, which occurred June 8-9, was the largest and most devastating and is the event that will be modeled in this study.

The watershed was divided into 27 sub-watersheds, all with an outlet located on 29-mile long main channel. Three different hydrological methods are used to compute the runoff hydrographs for each sub-watershed. These methods are Snyder's synthetic unit hydrograph within GIS, 1D diffusive-wave overland flow with Green and Ampt infiltration, and a calibrated SWMM model for the watershed using the Horton method for infiltration.

The parameters for Snyder's method, C_p and C_t, were previously calibrated for a single sub-watershed in the larger Greens Bayou watershed. These values are .39 and 1.8, respectively.

Inputs for the 1D overland flow model were a DEM (30-m from the USGS), land use/cover (30-m NLCD), and soils data from the NRCS (STATSGO). The infiltration values were determined using the average values from Rawls et al. (1983) for each soil type. The roughness values were determined from McCuen (1998) for each land use type.

The rainfall for this event was obtained from 14 rain gages dispersed in the Green's Bayou watershed. A hyetograph was created for each of the sub-watersheds using thiessen polygons and an area-weighted average method, and was used as input for all three models. Once hydrographs were generated using the hydrologic models for each of the sub-watersheds, SWMM was used to route the hydrographs to the watershed outlet, using the surveyed cross-sections from the calibrated SWMM model.

Results and Discussion

Each model was simulated using the same storm event. Data from USGS stream gage 8076700, located at the outlet of the Greens Bayou watershed, was obtained in order to compare the simulated hydrographs at the outlet to the observed hydrograph for Tropical Storm Allison. Results for the calibrated SWMM model, Snyder's method, and the 1D overland flow method are shown in Figure 2.

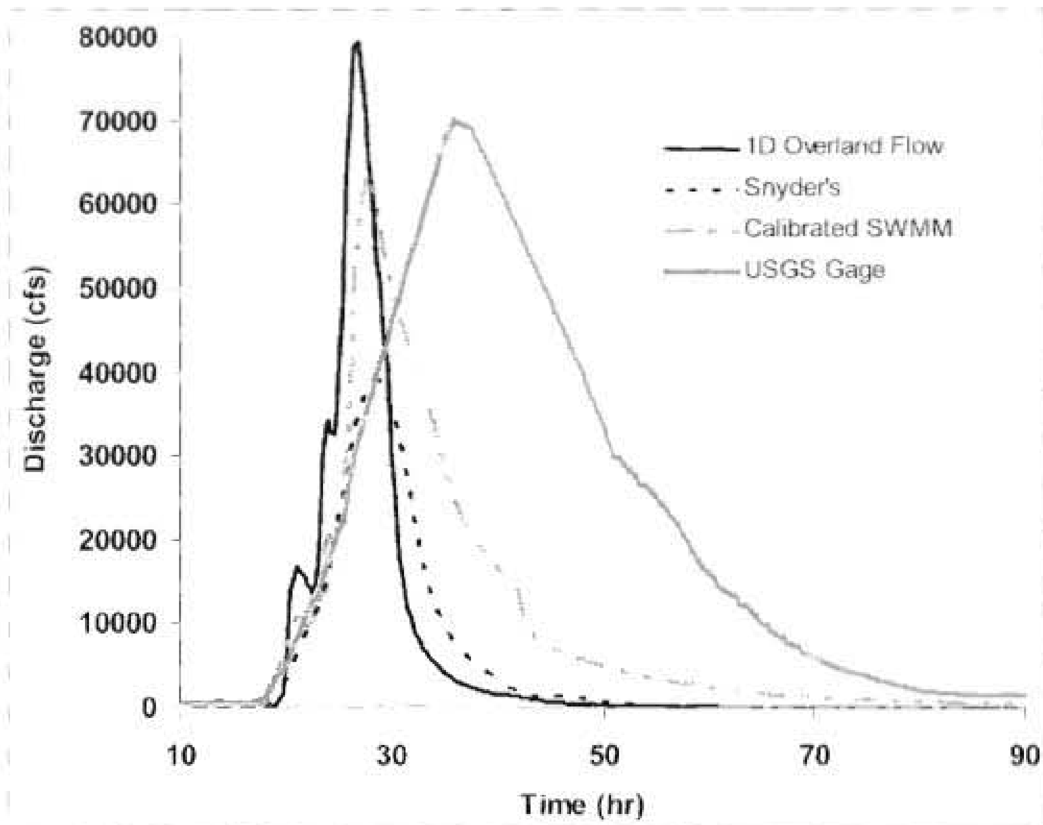

Figure 2- Calibrated SWMM model vs. USGS stream gage

An assessment of model performance compared to the observed gage data was made using the fit of the peak discharge in terms of root-mean square error (RMSE), bias, volume change, and percent change in peak discharge and time to peak. The results of this statistical analysis are shown in Table 2.

Table 2. Statistical Summary of hydrologic\hydraulic models

Model	RMSE (cfs)	Bias	Volume Change (acre-ft)	% Difference in Time to Peak	% Difference in Peak Discharge
SWMM	18179	-9012	81141	-24	-9
Snyders	22777	-12766	114448	-21	-44
1D Overland Flow	25104	-11886	106558	-25	14

This analysis shows that there is not a significant difference between the performance of the calibrated SWMM model and the 1D overland flow model. Overall, all models show that the total discharge volume modeled is less than the observed volume and the time to peak is early in all models. Causes for an early peak may be, but are not limited to, the rainfall data and the roughness values used for channel routing.

As expected, the Snyder's unit hydrograph model performed the worst when compared to the observed hydrograph. While the model was calibrated for one sub-watershed in the Greens Bayou, it is clear that further calibration is need when modeling the entire watershed. Though the results may not always be as accurate as using other methods, the model does provide a quick analysis which is beneficial for flood mapping and damage estimation.

The 1D overland flow model, using average values for infiltration and roughness parameters, performed very similar to the calibrated SWMM model. This model required no calibration and was simple and quick to set up. As with all of the models tested, the volume for the 1D overland flow model was much less than that of the observed hydrograph and the time to peak was early. There are several possible contributions to these deficiencies. The lack of volume may be attributed to infiltration parameters. Average values of hydraulic conductivity, initial soil moisture content, and wetting front depth were selected based on soil type. Deviating slightly from the average may decrease the infiltration rate, thus producing more runoff. Another contributing factor may be the inability of the model to significantly reduce the infiltration rate when a maximum infiltration volume has been reached for the specific soil types.

The current method for flood mapping uses only the peak discharge value. Therefore, the 1D model has shown that it can be very valuable to use. The peak discharge modeled in this study is within 14% of the observed peak discharge. Most importantly, this model required no calibration to obtain these results which makes this possible to use anywhere soil, land use, and topography data is available with little preparation time.

Conclusions

This second-order prediction approach is the second step in the development of a comprehensive extreme flood prediction and damage assessment simulation toolset. The Green-Ampt infiltration excess runoff prediction and 1D diffusive wave overland flow routing module, as well as the dynamic wave routing module with SWMM are significant improvements. Currently, the distributed hydrologic model is being improved using Green-Ampt infiltration excess runoff prediction and a 2D diffusive wave overland flow routing module. In addition, flood inundation mapping is being replaced with a 2D floodplain flow model using hydrograph outputs from SWMM as boundary conditions.

References

Federal Emergency Management Agency (FEMA) (2006). "Multi-hazard Loss Estimation Methodology, Flood Model, HAZUS MR2, Technical Manual." Developed by the Department of Homeland Security, FEMA, Mitigation Division, Washington, D.C., under a contract with the National Institute of Building Sciences, Washington, D.C.

Kalyanapu, A. (2006). "Geographic Information System Based Wide-Area Distributed Hydrologic Model." M.S. Thesis, University of Utah.

Kalyanapu, A., Judi, D., Burian, S., Berscheid, A., Hodge, B., and McPherson, T. (2007). "Channel Morphology Tool (CMT): A GIS-based Automated Extraction Model for Channel Geometry." *Proc., World Environmental & Water Resources Congress 2007*, ASCE, Tampa, FL.

McCuen, R. H. (1998). Hydrologic Analysis and Design. Prentice-Hall, Inc., New Jersey.

Rawls, W. J., Brakensiek, D. L., and Miller, N. (1983). "Green-Ampt infiltration parameters from soils data." *J. Hydraul. Div.*, ASCE, 109(1), 62-70.