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By: **Jeffrey D. Colby,** Karen A. Mulcahy, and Yong Wang

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# Modeling flooding extent from Hurricane Floyd in the coastal plains of North Carolina

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## ABSTRACT

In this article two modeling approaches were developed based on the use of US Geological Survey digital elevation model (DEM) data. These models were utilized to delineate the extent of flooding induced by precipitation from Hurricane Floyd in a portion of Pitt County, North Carolina. The patterns of flood extent derived from the two models were compared to the extent of flooding indicated on a digital aerial photograph taken two days after peak flood levels had been reached. In addition, floodplain boundaries based on Federal Emergency Management Agency Q3 maps were compared to the extent of flooding on the aerial photo. Actual emergency response operations undertaken through the Pitt County Emergency Operations Center during the flood event are described, and are used to provide a context for evaluating the potential utility of these models. The flood extents produced by the modeling methods performed well at representing the actual extent of the flooding.

## INTRODUCTION

Three million people were evacuated along the southeast coast of the United States in 1999 due to Hurricane Floyd (USACE and FEMA, 2000). This was the largest evacuation in US history ( FEMA, 2000). The US Army Corps of Engineers (USACE) and Federal Emergency Management Agency (FEMA) conducted an evacuation assessment study after Hurricane Floyd. The first major recommendation of their report cited the need to develop inland flood modeling capability for emergency managers and hurricane evacuation studies ( USACE and FEMA, 2000).

During the course of a large flood, covering an extensive area and taking place over several days, information regarding the current and predicted extent of flooding is needed to plan for rescue and relief efforts and to alert the community to hazards such as road closings (e.g., Corbley, 1993). A geographic information system (GIS) could serve an important role in a community's post-event emergency responses, by documenting road closures and infrastructure damage and by creating maps to guide emergency personnel across damaged landscapes ( Mileti, 1999). Unfortunately, few methods are available to emergency managers to determine the real-time extent of flooding or to aid in predicting the level to which floodwaters will rise in subsequent days. In some cases, officials rely on anecdotal evidence such as call-ins from emergency personnel and citizens to develop a characterization of flooding. Relying on spatially and temporally limited external sources of information regarding the extent of flooding, however, places emergency personal in an inefficient, reactive mode of operation. Methods for representing forecasted, real, or near real-time flooding extent using digital elevation models (DEM) in a GIS could provide a more accurate and useful depiction of flooding.

In this article two modeling approaches based on the use of US Geological Survey (USGS) DEM data were developed. These models were utilized to delineate the extent of flooding induced by precipitation from Hurricanes Dennis and Floyd in a portion of Pitt County, North Carolina. The patterns of flood extent derived from the two models were compared to the extent of flooding indicated on a digital aerial photograph taken two days after peak flood levels had been reached. In addition, the 100 and 500-year floodplain boundaries from FEMA Q3 maps, and the 100-year boundary with a quarter-mile buffer were compared to the extent of flooding on the aerial photo. Actual emergency response operations undertaken through the Pitt County Emergency Operations Center (EOC) during the flood event are described, and are used to provide a context for evaluating the potential utility of these models.

### Study area

Pitt County is located approximately in the center of the eastern coastal plain of North Carolina and covers 656 sq miles of prime agricultural land. The coastal plain drops only about 60 m in elevation as it extends 120–160 km from the Piedmont region in the middle of the state to the coast. Flat broad floodplains are located on the north side of the four large elongated river systems that drain the coastal plain, which includes the Tar/Pamlico River drainage that encompasses much of Pitt County. Sixty-three percent of the soils in Pitt County are characterized primarily as poorly or extremely poorly drained, with moderately well- to well-drained soils covering the remaining areas (Gares, 1999). The land surface in Pitt County has very low relief and extensive areas have been drained, cleared, and ditched for agricultural use. Higher ground is usually located on the southern side of the rivers, and the county's highest point, located in the northwest portion of the county, is 38.5 m above sea level.

The total population of Pitt County was 126,263 according to the results of a Special Census conducted in April 1998. The county's largest city, Greenville, is centrally located within the county and has a population of 56,788. The Greenville Metropolitan Statistical Area is the commercial, educational, medical, and cultural center of eastern North Carolina. The Pitt County/Greenville area is one of the fastest growing urban centers in the state of North Carolina. The local economy is diversified with government, wholesale/retail trade and manufacturing each accounting for approximately 25% of total employment. Agriculture is also a strong contributor to the economy; tobacco, corn, soybeans, wheat, peanuts, eggs, livestock, poultry, and vegetables are the primary agricultural products (Pitt County Development Commission, 2000).

The majority of the flooding in Pitt County that followed Hurricane Floyd was located in the broad primary and secondary floodplains extending northward from the main channel of the Tar River. Near the City of Greenville, the floodplains closest to the river were occupied by conservation and open space land uses. Continuing northward, low and medium density residential, industrial, and mixed land uses dominated. In Greenville, numerous areas were flooded including residential and industrial areas, the Pitt/Greenville airport, the water treatment facility, and the main power transmission substation (Colby et al., 2000; Wang et al., 2001) ( Fig. 1).

Fig. 1. Flooding along the Tar River in Greenville. View is towards the south with the power substation seen here on the left surrounded by booms. The Tar River channel is hidden beyond the trees but downtown Greenville and the East Carolina University Campus dormitories can be seen on the far side of the river. (Source: Pitt County Management Information Systems).

The area chosen for this study included a section of the Tar River that passed through the City of Greenville in Pitt County, North Carolina (Fig. 2). This area was selected for evaluating the methods for modeling flood extent due to its proximity to Greenville, and because a digital aerial photograph documenting the flooding was available from the North Carolina Department of Emergency Management (NCDEM). The extent of flooding that occurred in this area was indicated on the composite photograph, which was taken two days after peak flood stage had been reached on 23 September 1999.

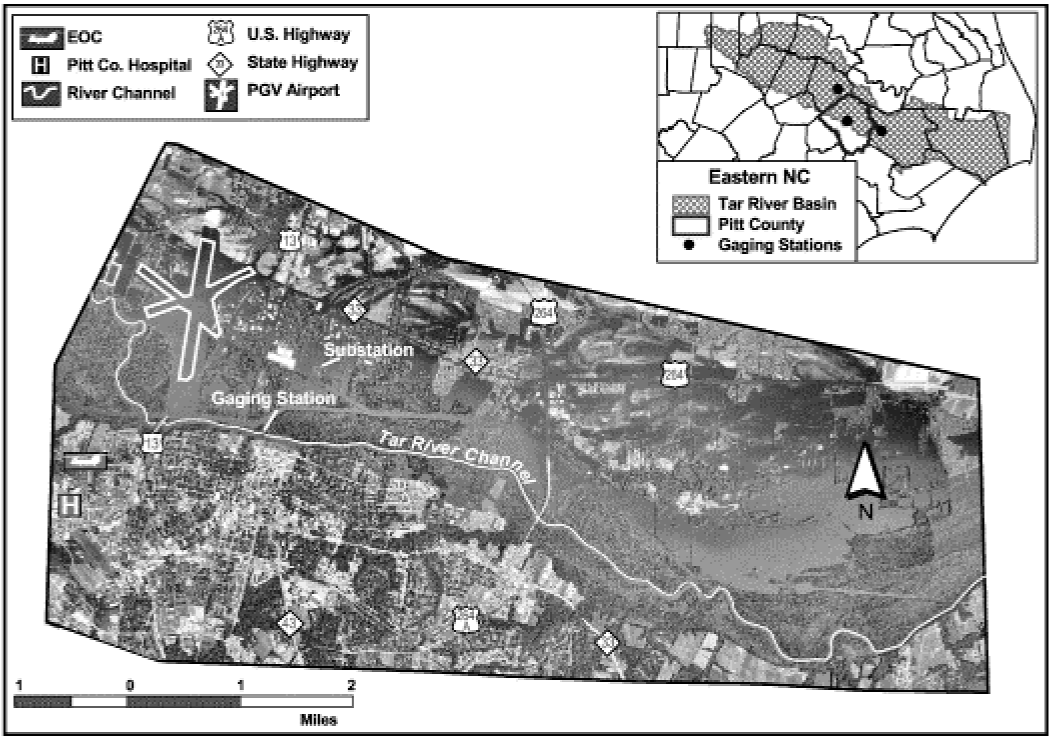


Fig. 2. An aerial photograph of flooding along the Tar River, September 23rd, 1999 covering the study area with significant features indicated. Locator map indicates the Tar/Pamilco River basin within eastern North Carolina and the location of Pitt County.

### Hurricane Floyd

In September 1999, eastern North Carolina was hit twice by hurricanes. First, Hurricane Dennis arrived as a very slow moving storm with only an 8–10 mph forward speed. Making landfall at Cape Hatteras, NC, on September 4, Dennis dumped 8–10 in of rain east of Interstate 95. Less than two weeks later, Floyd made landfall at Cape Fear, NC dumping another 10–20 in of rain east of Interstate 95. In the space of only two weeks, parts of eastern North Carolina received up to 30 in of rainfall, or a full 60% of the 48 in yearly average.

The flooding that followed the back-to-back visits of Hurricanes Dennis and Floyd caused extensive damage in eastern North Carolina. The depth of flooding and the number of homes damaged were greater than from any other natural disaster in North Carolina's history. Numerous communities were isolated and became inaccessible by land as massive damage was caused to North Carolina's highway infrastructure, including major highways and local routes (Batchelor et al., 2000). On September 15, President Clinton granted Emergency Declaration FEMA-3146-EM that authorized debris removal and emergency protective measures for 66 counties in North Carolina. On September 16, the Major Disaster Declaration FEMA-1292-DR was granted for the same counties, authorizing public assistance, individual assistance, and hazard mitigation.

**Pitt County Emergency Operation Center**

Headed by the Director of Emergency Services, numerous agencies or groups had direct responsibilities in the Pitt County EOC once it was activated to respond to the emergency event. Pitt County agencies that participated in the EOC after Hurricane Floyd included: Emergency Services, E-911, Management Information Systems (MIS), Sheriff's Department, Health Department, Department of Social Services, Mental Health Department, Pitt County Memorial Hospital, Pitt County Schools, the County Manager's office, as well as the Red Cross. The North Carolina State Highway Patrol, State Emergency Response Team, and pilots from the North Carolina Forestry Service were active in the EOC along with various other state agencies. Federal agencies included: the National Guard, FEMA, and pilots from all branches of the United States Armed Forces. Representatives from the City of Greenville and local municipalities eventually participated in EOC activities. The EOC was active 24 h a day for 18 days, and thereafter for additional partial days.

As the rains and high winds from Hurricane Floyd subsided, EOC officials began to realize that water levels were rising and that a major flood event was beginning. Floodwater height predictions began to be received from the National Weather Service (NWS). The immediate concerns for the EOC were determining where the floodwaters were rising, and finding locations where people would be safe. Knowledge regarding the current and predicted spatial extent of the flooding would have been immensely helpful in reducing the initial panic and stress. This knowledge would have provided critical information for warnings and directing evacuations, guiding the movement and management of key resources, and guiding the execution of rescue and relief efforts. A GIS operated by MIS supported many of these tasks. However, the technology was not fully integrated into EOC activities; modeling the spatial extent of the flooding using digital elevation data was not attempted due to a lack of topographic data and modeling expertise.

Evacuation warnings were carried out by EOC officials going door-to-door to notify residents. Potential flood warnings were based on the 100-year floodplain map provided by the MIS GIS. As floodwaters rose, the “evacuation line” was moved back one half mile. Access to a more accurate representation of the predicted extent of flooding would have assisted more efficient and effective notification efforts. In particular, this information would have improved the capability to determine where and when to order mandatory evacuations. Approximately 100,000 phone calls were handled by the EOC. Many of the initial calls were from citizens reporting rising water levels. Soon thereafter callers began inquiring about how and where to evacuate.

EOC officials found it difficult to communicate the best evacuation routes to callers, as one of the most difficult tasks at the EOC was keeping track of road closings and openings. Citizens, deputies, and state troopers would call in to the EOC to report flooded roads. Additional reports came through E-911 and the North Carolina Department of Transportation (NCDOT). Although information provided by the NCDOT during the hurricane was very helpful, conflicting information was sometimes provided by different state agencies (i.e., NCDOT, State Highway

Patrol), and NCDOT field forces found it difficult to simultaneously repair and report road conditions (Batchelor et al., 2000).

Information on road conditions was especially critical for E-911 dispatching. However, the numerous sources of road closure information were difficult to consolidate and provided only a partial representation of flood extent. In addition, it was rare to receive information on roads that had become passable. Road conditions were monitored using an analog map produced from the MIS GIS, which was hung on the wall of the EOC. A red “X” drawn on the map indicated an impassable road. When a road was determined to be passable, the “X” was circled in green. The ability to model rising and receding flood levels as well as water velocities across roads would have proven invaluable.

The protection and management of key resources would also have benefited from the ability to model the potential and actual extent of flooding. With sufficient early warning, significant resources could have been relocated. For example, the Greenville Utilities Commission (GUC) lost 77 vehicles and many documents to the quickly rising waters, and sustained $11 million worth of damage (R. Langley, pers. Comm., 2001, Superintendent GUC Water Treatment Plant). Preparations for the protection of infrastructure could have been enacted earlier, including the construction of sandbag walls around utility buildings and the placing of pumps. If it had been known in advance that the county was going to be cut in half by the Tar River, critical supplies stationed north of the river could have been moved to the south side where rescue and relief efforts were headquartered. Industries that were to be affected by the rising waters could have been notified in advance so they could prepare for and lessen the impact from a plant shutdown.

As floodwaters rose, people were encouraged to place calls for rescue through established hotlines rather than through E-911. It was believed that E-911 would best serve those that needed immediate medical attention. Rescue requests were routed through a Rescue Request desk in the EOC. Once a rescue was deemed necessary the information was passed onto the Sheriff's Department, which dispatched deputies and volunteers with boats to the area. If a rescue could not be made by watercraft, then the aircrews were contacted. Most of the aerial rescues were initiated when helicopters spotted people in obvious need of assistance. An Air Force AWACS aircraft coordinated the large quantity of helicopter air traffic. Over 2000 rescues were performed in Pitt County by air, boat, or land-based vehicles.

GIS technology was used to help guide emergency and rescue operations. The E-911 Communication Center relied heavily on GIS to perform their task of taking an emergency call, determining the appropriate response, and dispatching the responder within 32 s. The GIS informed the dispatcher of the location of the caller, and which first and secondary responders were responsible for that area. Countless maps were generated by the MIS GIS to guide boat rescues and were faxed to National Guard and volunteer personnel in the field. In addition, latitude and longitude coordinates were generated from incoming rescue calls and provided to helicopter pilots. During these rescue efforts, maps of the current and predicted spatial extent of the flooding would have aided in planning the allocation of resources, such as boats, and in land

and water-based navigation. Also, the capability to model receding flood waters would have been useful in locating populations that remained stranded, thereby assisting in relief efforts.

In addition to creating maps for navigation, the MIS GIS was used to calculate damage estimates. The flood extent represented by the 100-year floodplain map buffered by 1/4 mile was combined with the county parcel coverage to derive damage estimates to structures within the county, information that was requested by and provided to FEMA. A list of homeowners was also generated from overlaying the floodplain map with the county parcel coverage, and was used to seal off affected areas and to verify property owners.

As documented in the Pitt County example described above, during the response phase of a large flood event, a GIS could serve a useful purpose in mapping disparate information in order to depict where floodwaters may be rising, and what roads may be closed. In Pitt County, if this incoming information had been consolidated into one GIS database, updated from a single source, and had been made available to emergency response personnel either through a server to multiple terminals or even displayed on the wall in the EOC, an improvement in monitoring the extent of flooding and in emergency response efforts would have been achieved. Relying on information from external sources, however, placed emergency personnel in Pitt County in a re-active rather than pro-active mode of operation (P. Sullivan, pers. Comm., 2000, Pitt County Management Information Systems). In addition, the information from these sources was incomplete both spatially and temporally and provided only a partial characterization of the flooding.

## FLOOD MODELING METHODOLOGY

The application of GIS in the field of water resources research and management is growing, as the utilization of spatial data is integral to these activities (Wilson, J., Mitasova, H. and Wright, D., 2000. Water resource applications of geographic information systems. URISA Journal 12 2, pp. 61–79.Wilson et al., 2000). More specifically, the linkage of GIS and hydraulic/hydrologic modeling for floodplain and flood extent mapping has been under study (e.g., Hill et al., 1987; Pandyal and Syme, 1994; Boyle et al., 1998; Correia et al., 1998; Townsend and Walsh, 1998; Chang et al., 2000; Olson et al., 2000; Yang and Tsai, 2000). However, few studies have discussed the application of this linkage for operational flood forecasting as suggested by Smith and Ward (1998). A GIS could be used to extract information from digital elevation data for input to a hydraulic model, and then used to map the potential or current spatial extent of floodwaters.

Two methods for delineating the extent of flooding on 23 September 1999 were examined and compared to the representations of flooding that were available and used by the Pitt County EOC. The first method was based on implementing a hydraulic extension program called HEC-GeoRas3.0 (USACE, 2000) within the ArcView 3.2 GIS software ( ESRI, 1999). Parameters were extracted using the hydraulic extension program and input into a hydraulic model called HECRAS 2.2 ( USACE, 1998). Water surface profiles for the study area were generated in HECRAS 2.2. Manual methods for deriving hydraulic model parameters for floodplain delineation, through field surveying or the use of analog topographic maps, are time consuming.

The development of programs to simplify the derivation of parameters for hydraulic modeling in a GIS (e.g., Ackerman et al., 2000; Dodson and Li, 2000) has increased the efficiency and accuracy of deriving these parameters ( Dodson and Li, 2000). In the second method, a digital elevation model (DEM) was inundated based on the interpolation of water surface level measurements recorded at USGS gauges. The flood extent patterns derived using these methods were qualitatively compared to the pattern of flooding found on a composite digital aerial photograph.

## Data

The primary spatial data that were used for generating flood extent using the first two methods were 7.5-min level 2 USGS DEM quadrangles, which were freely available for downloading via the Internet from the USGS. The easy access and comprehensive coverage of USGS DEMs across the US provided the rationale for using them to test the flood modeling methods even though other higher resolution elevation data exist for the creation of DEMs, such as airborne light detection and ranging (LIDAR) data (e.g., Jones et al., 1998) or interferometric synthetic aperture radar (IFSAR) data (e.g., Sanders and Tabuchi, 2000; Sugumaran et al., 2000). A mosaic of four 7.5-min quadrangles was created, and the study area was subset from the mosaic.

Within the study area, the elevation ranged from 0 to 26 m above sea level. The ground resolution (x, y) was 30 by 30 m. The elevation interval (z) was 0.30 m, with a root mean squared error of 1 m.

Other data used in this research included digital orthophoto quadrangles (DOQ) and hydrologic data, both of which were available from the USGS. DOQs are digital versions of aerial photographs in which the displacements caused by the terrain and the camera have been removed. The DOQs for this study were taken in 1993, and had a ground resolution of 1 m×1 m. Hydrologic data (water level and discharge) from three gauge stations near and within the study area were obtained from the USGS.

## GIS/hydraulic modeling

For floodplain mapping, linkages have been developed between GIS and hydraulic models, particularly with some of the NexGen models produced by the US Army Corps of Engineer's (USACE) Hydrologic Engineering Center (HEC) (e.g., Ackerman et al., 2000, Kraus, 2000). In this study the HEC-GeoRAS 3.0 program, operated in the GIS ArcView, was used to create a parameter file for input to HEC-RAS 2.2 hydraulic model. The parameter file is essential for proper functioning of the model; it describes stream, flowpath, cross-section, and land surface characteristics. HEC-RAS 2.2 provides the capability to perform steady flow water surface profile calculations, and has been approved by FEMA for use in the National Flood Insurance Program (NFIP).

A sequence of steps was followed to generate water surface profiles that were then displayed in the GIS software. First, the DEM data were converted to a triangulated irregular network (TIN) format. Next, using the HEC-GeoRAS 3.0 extensions program, and the TIN elevation file as background, linear features such as stream centerlines, main channel banks, flowpath centerlines, and cross-section cutlines were entered by digitizing or tracing them on the computer screen with the mouse as input device.

These features were collected in a ‘geometric import file’ and imported into the HEC-RAS 2.2 analysis program. The Manning's roughness coefficients (Chow, 1959) required for modeling were initially calculated automatically using the HEC-GeoRAS 3.0 extension program and a land use data layer in the GIS software. Ultimately, in this study, the roughness coefficients were estimated based on land cover interpreted from DOQs. Along with the geometric input file, daily mean discharge and water surface level data were entered into the HEC-RAS 2.2 program. Water surface profiles and velocity data were generated and then displayed in the ArcView 3.2 GIS software. The pattern of flooding from the GIS/hydraulic modeling method was overlaid on the aerial photograph to qualitatively assess the accuracy of the derived flood pattern ( Fig. 3a).

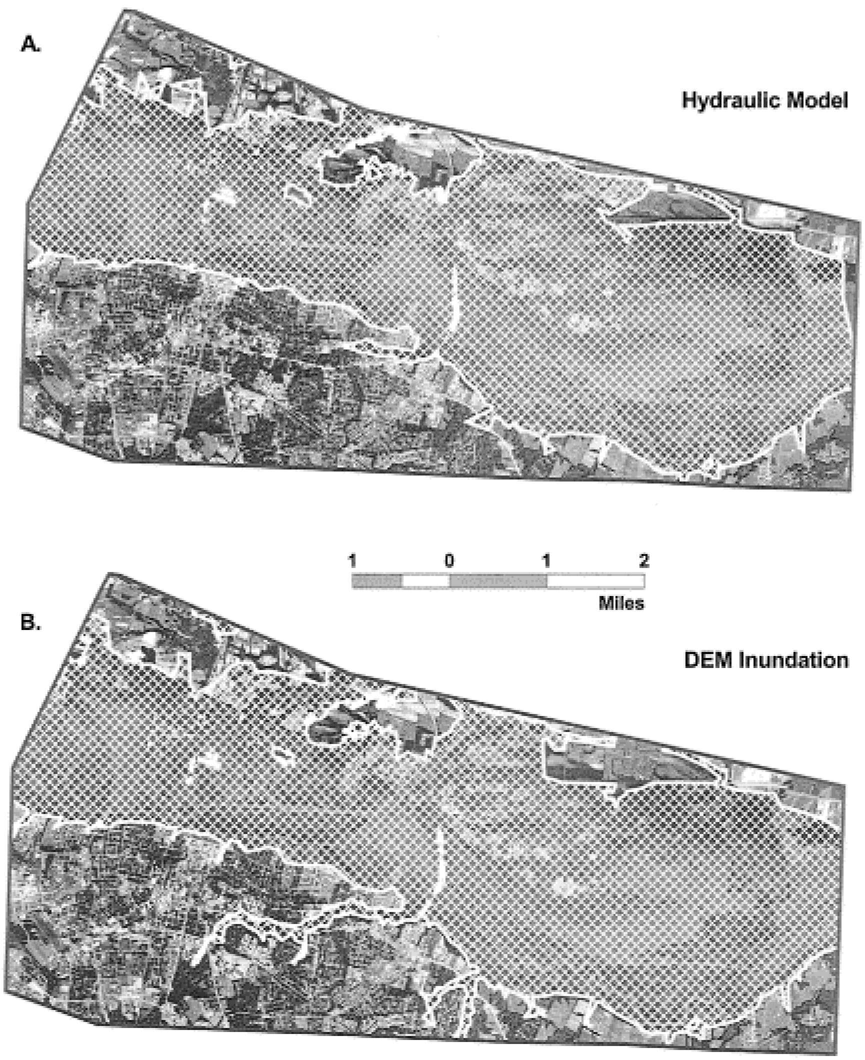


Fig. 3. Predicted flood extent patterns overlayed on aerial photograph: (a) GIS/hydraulic modeling results and (b) DEM inundation results.

## DEM inundation

The second modeling approach used to determine the extent of flooding was inundating the DEM data using a GIS by stage height data available from USGS gauges. This method was developed with the intention of evaluating its utility for quickly and efficiently representing the level of flooding. Data from three gauge stations on the Tar/Pamlico River were used: (1) Tarboro, in Edgecombe County, about 16 km upstream and northwest of Pitt County, (2) Greenville, located near the center of Pitt County, and (3) Washington, located several kilometers to the east of Pitt County. The water surface height was obtained and referenced to sea level at each gauge station. A linear interpolation method based on distance (stream length) estimated the water level between gauge stations. In general, an estimate of water surface height based on drainage area would be more appropriate for inundating the DEM rather than a linear estimate of stage level between stations (B. Pope III, pers. Comm., 2000, USGS office at Raleigh of North Carolina). In this study area, the relationship between stream length and drainage area appeared to be approximately 1 : 1, and stream length was used as an acceptable surrogate for drainage area.

The actual surface water heights were based upon a piecewise linear interpolation of stream segment lengths along the Tar River. An efficient process to implement this method entailed the following: (1) subset the DEM into small segments based on stream length, (2) recode each segment separately based on the interpolated water surface height at that segment to create a thematic layer of flooded and non-flooded areas, and, finally, (3) mosaic all thematic layers together to create the final inundation map for the study area. For this study, 18 segments along the Tar River, between Tarboro and Washington, were subset and 18 flood surface water heights were derived and used to inundate each segment. The average distance of the 18 segments was about 3 km, and the average water surface height difference between segments was approximately 0.67 m. The area flooded using this method was overlaid on the aerial photograph (Fig. 3b).

**Q3 floodplain boundaries**

The digital versions of FEMA flood insurance rate maps (FIRM) are referred to as Q3 data. Newer digital flood insurance rate maps (DFIRM) are scheduled to replace the Q3 data. However, in Pitt County Q3 data were the only digital floodplain data available during the flood. As it became clear that the floodwaters were rising past the 100-year floodplain, the extent of flooding was estimated to extend approximately 1/4 mile beyond the 100-year floodplain boundary. At the request of EOC officials, MIS GIS personnel extracted the “A” and AE” zones from the Q3 data. These two attribute values in the database represent the predicted 100-year flood zone. To this zone, a GIS function called buffering was employed to uniformly extend the 100-year boundary line by 1/4 mile. The 100-year floodplain and the extent of flooding based on the buffered boundary were overlaid onto the digital aerial photograph of the study area (Fig. 4a and b).

## RESULTS

**GIS/hydraulic modeling**

The pattern of flooding generated by the GIS/hydraulic modeling approach, seen in Fig. 3a, reasonably replicates the actual pattern of flooding on 23 September 1999. The extent of flooding on the southern side of the river closely matches the pattern of flooding according to the aerial photograph. The accuracy in matching flood levels in this area can be attributed, in part, to the greater relief on the southern side of the river that creates a more definitive flood line. Flooding in the tributaries on the southern side of the river is not indicated because the cross-section cutlines, digitized perpendicular to the river and used for hydraulic modeling, did not cross the tributaries. On the northern side of the river the areas represented as flooded by the GIS/hydraulic model reasonably match the flooded area as depicted on the aerial photograph, and only a small segment along Highway 33 and some agricultural acreage are not indicated as flooded. These areas are small, however, compared to the total amount of flooded area.

A potentially significant source of error in water surface profile generation is the subjective estimation of Manning's roughness coefficients (USACE, 1986; Dodson and Li, 2000). Initially, in this study land use data classified from a Landsat TM image (30 m×30 m resolution) were utilized to derive Manning's roughness coefficients for hydraulic modeling. The coefficients estimated using this approach did not provide a reasonable flood extent approximation. The poor representation of flooding extent may have been due to several factors including the thematic classification accuracy of the land use categories, inaccurate estimates of roughness coefficients for a given land use type, the georeferencing accuracy of the data layer, or the coarse resolution of the data layer. Therefore, higher resolution (1 m×1 m) land cover information represented on a DOQ was used to estimate the coefficients in this study.

Significant calibration of the model was not undertaken because calibration sources such as the aerial photograph would not be available during a flood event. Additional calibration of the model (e.g., adding cross-sections, and adjusting roughness coefficient estimates) could be undertaken to refine the flood extent boundaries. When flood extent information is available from previous events, the model could be calibrated before the next flood event. During the next event, forecasted or ‘real time’ discharge and water level data could then be input to the model, and the flooding pattern immediately generated.

**DEM inundation**

The pattern of flooding generated through inundating the DEM is depicted in Fig. 3b. The pattern appears similar to that generated using the GIS/hydraulic model. Some small differences exist near the airport, and north of US Highway 264 in the northeastern segment of the photograph. Generally, the derived pattern of the flooding along the river reasonably approximates the actual extent of flooding. Again, this method could be developed preceding a flood event, and during a flood the forecasted or current stage level data could be entered as it became available.

**Q3 floodplain boundaries**

Depictions of the 100-year Q3 floodplain boundary and the 1/4 mile buffered boundary were included to provide a representation of the floodplain boundaries that are commonly used for flood insurance purposes, and the extended flood estimate used by EOC officials. As seen in Fig. 4a, the 100-year floodplain boundary underestimated the extent of flooding in some areas (the western part of the photograph, and north central part of the photograph near the bridge) and overestimated the extent of flooding in the eastern part of the photograph.

The magnitude of flooding in this area may have been greater than a 100-year event. Flood recurrence intervals were re-calculated by the USGS after Hurricane Floyd for the Tarboro station, which experienced a greater than 500-year event (Bales et al., 2000). Therefore, we extracted and overlaid the Q3 500-year floodplain boundary on the aerial photography. The only significant difference between the pattern of the 500-year floodplain boundary and the 100-year boundary was that the north-central portion of the photograph was represented as flooded for a 500-year event.

The 1/4 mile buffer added by EOC officials can be seen (Fig. 4b) to significantly overestimate the extent of flooding in this study area. Moreover, the extent of overestimation is not consistent. For example, the flood extent boundaries along the tributaries of the Tar River in the southern portion of the photograph are excessive. Although this estimate was the best available at the time of the flooding, the distance based buffer did not accurately represent the extent of flooding as well as the hydraulic modeling or DEM inundation approaches.

## DISCUSSION

### Pitt County EOC

The ability of Pitt County EOC officials to represent current and forecasted flooding extent caused by Hurricane Floyd based on digital elevation data would have provided significant benefits both during and after the flooding. The establishment of reliable modeling capability would enhance methods for public notification and warnings through the news media and the world wide web (e.g., Sugumaran et al., 2000). Also, new GIS software programs (e.g., Dialogue Communications, 2001) are being developed that would support notification of potential flooding hazards by phone.

An accurate representation of potential flooding would assist in the management of critical resources in Pitt County. For example, using a GIS, areas that are expected to be flooded could be compared to known demographic data. The derived information could provide estimates for resources and personnel needed for shelters, such as total amounts of basic food and water resources, language translators, baby food and supplies, and special medical needs. Improvements in post-flood damage assessments could also be realized through modeling the extent of flooding using the methods described in this paper, rather than relying on arbitrary estimates of flooding extent.

### Model comparisons

The GIS/hydraulic model can be calibrated using up-to-date land cover coefficients, well-designed cross-section cutlines, and prior flood extent data. This capability can provide a more refined representation of flooding extent. If discharge data are available or can be reliably estimated for a tributary, the tributary drainage can be incorporated into the modeling process (e.g., Ackerman et al., 2000). In addition, velocity profiles can be generated which could have been useful in determining the strength of the current flowing across roads as was requested by emergency managers.

Some background in hydraulic modeling is recommended before utilizing the HEC-RAS 2.2 program (USACE 2000). This recommendation is a possible disadvantage as few municipal or county planning personnel are likely to possess this type of background and training may be required to fully utilize the GIS/hydraulic modeling approach.

Advantages to the DEM inundation modeling approach are that the model is simpler to execute and requires only stage level data as hydrologic input. However, in areas with greater relief and topographic variability accurate interpolation between gauges may be more problematic. This method may be most applicable in areas of low relief such as the coastal plains (Colby et al., 2000; Wang et al., 2001). Other limitations of this method are that tributaries are only flooded according to water height from the main channel and the actual flows through the tributaries are not modeled.

**Data limitations**

Perhaps the most significant limitations to the application of these models for emergency flood response are those imposed by data quality and temporal and spatial availability. The flood extent boundaries generated by the two primary modeling methods used in this study cannot claim an accuracy level greater than the estimated error of the DEM data. Therefore, some caution should be used in evaluating flood extent boundaries within this range. Few studies have been undertaken regarding how to best represent the potential accuracy of DEM data in representing floodplains (e.g., Hunter and Goodchild, 1995), and standard methods have not yet been developed for quantitatively evaluating the horizontal extent of floodplain boundaries. Comparison of floodplain boundaries to ground truth information, such as aerial photographs, is invaluable for verifying accuracy. The level 2, USGS DEM data, even with a vertical error range of ±1 m, represented the extent of flooding reasonably well in the study area.

New sources of higher resolution elevation data for the state of North Carolina are anticipated which should increase the accuracy of the modeling efforts described in this paper. North Carolina has recently been designated as FEMA's first Cooperating Technical State (CTS) (Dorman, 2000; FEMA/NC Agreement, 2000). As a CTS North Carolina will assume responsibility for developing its own FIRM products. High resolution DEMs will be produced for the entire state based on airborne LIDAR data.

The spatial and temporal availability of hydrologic data, (i.e., stage level, discharge) strongly affects the utility of the models proposed in this paper during a large flood event. In response to flooding from Hurricane Floyd, 2–3 h flood stage forecasts were received by the EOC from the NWS. Discharge can be estimated based on a rating curve from river stage level. Flood stage forecasts were available for the Tarboro and Greenville stations on the Tar River, but not downstream for the Pamlico River at Washington. The USGS provides “real-time” stage and discharge data on the world wide web (USGS, 2001) for all three stations, but does not provide forecasts. During a flood event a USGS gauge may become inoperative, but efforts are made to collect data using backup systems ( USGS, 2001). The availability of hydrologic data may determine the opportunity to forecast and monitor the spatial extent of floodwaters during a flood.

The temporal availability of hydrologic data would also determine the task for which these types of modeling efforts could be useful. The time frame required for representing flooding extent ranged from minutes to hours for E-911 response to 24–48 h for the majority of EOC operations. E-911 response time needs were of a much shorter duration; they may need to send in a land-based rescue team and to know how much time the team had before they would be cut off due to rising waters. This point was illustrated by cases of state troopers who drove down a section of road, reported it open, and were blocked by floodwaters upon their return. These events occurred during flooding of the Tar River and were not due to flash flooding.

### Further research

One approach to circumvent reliance on hydrologic data during a flood would be to first calibrate and validate the models. Multiple flooding scenarios could then be created to represent a range of potential conditions at various stage levels. During a real event, the flood maps created in this manner could then be “pulled off the shelf” and used, based on a decision criteria matrix of hydrologic conditions and hydro-climatological forecasts. Reports from the field could be used to validate and adjust flood extent representations.

Additional investigations should be undertaken to apply these methods to areas of larger spatial extent. The study area in Pitt County was limited to an area near Greenville. To monitor road closings for a larger area, studies should be undertaken to model flooding for entire counties, watersheds and drainage basins. The complexity of the modeling exercises will increase as spatial extent and topographic variability increase.

## CONCLUSIONS

The linkage of GIS and hydraulic/hydrologic modeling for operational flood forecasting has not been well studied. However, new software programs have become available that encourage the development of this linkage for modeling forecasted, real, and near real-time representations of flooding extent. This paper has explored the benefits that might be provided by, and the potential for, developing an inland flooding model using GIS technology and digital elevation data. The need for developing dynamic flood modeling capability was underscored by the Hurricane Floyd Assessment Report. The first major recommendation of the report was to build an inland flooding component into the hurricane evacuation study process (USACE and FEMA, 2000). The implementation of other recommendations, related to improving evacuation efforts would benefit from having access to the information generated from the flood modeling approaches described in this paper.

Either of the modeling methods that use digital elevation data would have provided the capability to accurately represent and monitor the spatial extent of the flooding following Hurricane Floyd in the study area. Both methods would have provided a solid foundation for incorporating information called in by citizens, deputies, state troopers, and provided by the NCDOT. Additionally, both methods performed better at representing the spatial extent of the flooding on 23 September 1999 than did the Q3 100-year or 500-year floodplain maps, or the 100-year floodplain map with a 1/4 mile buffer zone. The development of models for representing forecasted extents of flooding, and for monitoring rising and receding water levels, would provide emergency personnel with a pro-active tool for emergency response. With the increasing use of GIS in county and municipal planning, local officials in flood prone areas may want to use the most accurate floodplain estimates and flood extent-modeling methods available. In Pitt County, North Carolina, EOC officials would have welcomed access to the modeling approaches developed in this application, and the information generated from those models during the flooding caused by Hurricane Floyd.

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