NEXRAD Flood Warning System and Floodplain Library For Houston, TX

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Abstract

Early flood warning systems protect both infrastructure and human life by issuing accurate flood warnings to public and private entities, enabling emergency personnel to employ strategic procedures. One such system, the RiceU/TMC Flood Alert System (FAS) has proved effective at predicting flood levels along Brays Bayou for 30 major storm events since 1997, including T.S. Allison in 2001. The current flood alert version, FAS2, couples available radar data (NEXRAD) with real-time hydrologic models to predict peak flood levels with 2 to 3 hours of lead time, and issues warnings via the internet to emergency personnel. The FAS2 is also currently being expanded to other areas of Texas. The future installation of a distributed high-resolution CASA radar-sensing network (NetRAD) in Houston will increase the city's ability to forecast severe events and to direct emergency response at a street scale.

Existing hydraulic models developed by the T.S. Allison Recovery Program (TSARP) for Brays, White Oak and Buffalo Bayous that drain downtown Houston and the Texas Medical Center were revised and merged to analyze the coastal storm surge impacts to the inland drainage areas by incorporating hurricane induced storm surge data in Galveston Bay. The combination of storm surge data, accurate and current hydraulic models, and NEXRAD radar within a GIS framework demonstrated severe inundations in non storm surge zones including major evacuation routes from Galveston. The next generation flood warning system should incorporate storm surge information to better predict the impacts of severe storms on inland watersheds.

A unique aspect of this flood warning system is that a predictive floodplain library has been developed for the White Oak watershed in Houston; the library analyzes rainfall intensities and patterns to quantify water surface elevations and delineate floodplains under various spatial and temporal conditions. The development of the floodplain map library for Brays Bayou is currently on-going. FAS2 employs an algorithm that allows the library to dynamically link real-time rainfall observations to appropriate floodplain maps that have been pre-delineated using more than 100 combinations of rainfall variations, allowing the emergency personnel to quickly determine likely inundations and begin flood preparations with as much lead time as possible.

Introduction

Flooding is considered the number one natural disaster in the United States. According to the National Oceanic and Atmospheric Administration (NOAA) and National Climatic Data Center data for the period between 1980 and 2004, 28 out of 60 disasters occurred in 1990s and were directly flood related (NCDC, 2004). The average for flood damage costs in the United States was over \$4 billion annually (NWF, 1998), and has increased due to major events in 2004, and 2005. The type of floods that cause the greatest damage and loss of life are flash floods associated with intense rainfalls in urban areas. Damages can be excessive due to insufficient preparation and lack of lead-time available for emergency response personnel. The severity of the flood problem is clearly at the national level, even after years of investment in flood control (Bedient and Huber, 2002).

Major floods have plagued the Houston, Texas area for many decades, due to intense rainfalls combined with rapid urban expansion in the city. Ninety percent of the Houston rainfall events are convective storm systems (Schwertz, personal communication, 1998). The typical summer convective storms are extremely variable in space and time and can produce very intense rainfall rates that lead to localized flooding (Doswell *et al.*, 1997). The issue of flood warning and alert was brought to the forefront of public attention in Houston after the T.S. Allison flood of June, 2001. An estimated \$5 billion in damages and about 50,000 damaged structures were reported throughout the Harris County. The Texas Medical Center (TMC) alone accounted for nearly \$1.5 billion in damages resulting from flooding in Harris Gully near Brays Bayou. In such urban areas where option of constructing flood control infrastructures isn't available due to limited spatial conditions, flood warning system may have the greatest potential to reduce damage (Vieux, 2004; and Pingel and Ford, 2005).

The primary focus of the research is to achieve more accurate and timely flood forecasts for Houston by using real-time radar data and develop a hydraulic prediction feature based on a dynamic floodplain determination. Development of a floodplain map library system as a new hydraulic prediction tool for FAS2 is described, which is being integrated into the current flood warning system to provide real-time visualized data on flood inundation levels as rainfall occurs.

NEXRAD Radar and GIS Applications in Flood Predication

Flood alert systems have become increasingly necessary, especially in urban areas, due to the impacts that development has on flooding. During the late 1970s, the first of the Automated Local Evaluation in Real Time (ALERT) systems was developed by the National Weather Service at the California Nevada River Forecast Center to assist in the early notification of flooding. Since then, many more ALERT systems have been established throughout all parts of the United States. However, it is difficult for ALERT to detect floods at the watershed level with sparsely placed rain gauges given the extremes that can occur in spatial and temporal rainfall variability in the Texas Gulf Coast region.

The availability of the new NEXt Generation RADar (NEXRAD) (WSR-88D) for rainfall estimation and flood prediction greatly improves the spatial and temporal coverage of a watershed for prediction purpose. NEXRAD radar and other new technology such as automated data reporting dissemination via the Internet and advanced communication systems have made site-specific flood warning system possible. Bedient et al. (2000) reported on the accuracy of NEXRAD for flood prediction using HEC-1 in Houston, and found excellent agreement for several storm events including one of the first large floods (October, 1994) analyzed with radar data. Vieux and Bedient (1998) found that a tropical rainfall-reflectivity conversion (Z-R) worked better for October 1994 rainfalls than the standard relationship normally applied to frontal systems. It has long been recognized that rain gauges can be used to improve the accuracy of radar rainfall estimates (Ogden, 2000; Vieux, 2004). Adjusting radar data with gauge data is beneficial in reducing systemic errors in the radar-derived precipitation measurement and improving hydrologic prediction (Mimikou, and Baltas, 1996; Anagnostou et al., 1998; Johnson et al., 1999; and Baun et al., 2004). Sun et al. (2000) concluded that calibrating radar rainfall estimates with local rain gages could improve flood estimates. Vieux and Bedient (2004) suggested the need for bias-adjustment of radar in real-time to improve model accuracies to a satisfactory level. The calibrated radar data is used in the current version of flood alert system (FAS2).

A hydrologic analysis using spatially-oriented radar data, defined watershed boundaries, and other spatial hydrologic parameters is greatly enhanced by the use of Geographic Information System (GIS) (Maidment and Djokic, 2000; and Bedient and Huber, 2002). GIS can be linked with radar data to track storms over a particular area in real-time and to calculate rainfall rates within a subwatershed, either as part of a post-event analysis or in real-time. The linkage of NEXRAD and a GIS system gives the ability to estimate the amount of rainfall that has fallen over a specific watershed area. These watershed-level rainfall estimates can create a powerful system for storm prediction and flood alert using real-time hydrologic models, one of which is a lumped-parameter hydrologic model (HEC-1) (Bedient *et al.*, 2003).

Flood Alert Systems (FAS)

The availability of NEXRAD has enabled radar-based flood alert systems beginning in 1993. The Rice/Texas Medical Center Flood Alert System (FAS) as one of such has been in place for TMC and been available on the web (FAS) since spring of 1998. It has been operational during last 30 storm events; especially it successfully provided precise and timely information to TMC during T.S. Allison. The system focuses on Brays Bayou in southwest Houston, which is prone to flooding due to its location in the downstream part of a completely urbanized watershed. The first generation of FAS provided TMC with real-time rainfall patterns and predicted peak flows (from a hydrologic nomograph) in Brays Bayou, along with visual feedback in the form of a real-time camera system that records snapshots of water levels in the stream (Hoblit *et al.*, 1999; Bedient *et al.*, 2000, and Bedient *et al.*, 2003), which enables TMC to disseminate flood warning information to member institutions, to initiate plans for emergency response, and to implement flood response for its 22 member institutions and hospitals (Figure 1).

The current version (FAS2), which was built on the earlier system (FAS) since 2003, utilizes higher-resolution radar (NEXRAD) data (1 x 1 km) coupled with real-time hydrologic models to achieve more accurate, greater lead time, and timely flood forecast estimates. This project was funded by the Federal Emergency Management Agency (FEMA) and TMC after the T.S. Allison (June, 2001). FAS2 system includes radar rainfall, conversion to watershed rainfall, real-time hydrographs for flood peak predictions, and two real-time bayou camera images. One of the hydrologic models is HEC-1 developed by U.S Army Corps of Engineers. The reason for using HEC-1 model is because it provides convenience of scripting and stability during simulation compared with HEC-HMS. PreVieux, a quantitative precipitation estimating tool developed by Vieux & Associates, Inc., for approaching storms has been incorporated into the system for the purpose of developing quantitative flood forecasts with greater lead time. FAS2 also has created a series of emergency communication tools linked to the web site, which automatically delivers warning information to the emergency personnel at TMC via a variety of methods including pages, emails, cell phones, and faxes. Fang et al. (2007) evaluated the flood forecasting performance of FAS2 for 3 major events during 2006 season with excellent results.

Other two major urban watersheds (White Oak and Buffalo Bayous) drain through large urban areas both outside and inside the loop 610, and downtown Houston. In order to protect downtown Houston and most of the Houston area from flooding, these two watersheds are being investigated for development of flood warning systems. The following section will discuss more details about the hydrologic models for White Oak and Buffalo Bayou watersheds by TSARP.

TSARP

In the aftermath of T.S. Allison, FEMA and the Harris County Flood Control District (HCFCD) began a multi-year initiative called the Tropical Storm Allison Recovery Project (TSARP) that comprehensively assessed the flood risks associated with the major flooding sources within Harris County. Both agencies used innovatively scientific techniques to determine the current flood risks posed by streams and bayous throughout the county's approximate 4,300 km² area, including 22 watersheds and 35 communities. As a result of TSARP, not only were Harris County's floodplains entirely remapped, but brand new and more accurate data and computer models were created using important advances in science and technology.

The Brays, Buffalo, and White Oak watersheds have recently been evaluated as part of TSARP and the resulting hydrologic and hydraulic models formed the basis for development of the floodplain map library system. Since investigation of Brays and Buffalo watersheds is still under going, only some preliminary results of the floodplain map library for the White Oak watershed are presented in this paper.

Storm Surge in Flood Forecasting

Each year, during the hurricane season, the Gulf of Mexico is threatened by severe storms, which may cause severe storm surges. A Category 4 or 5 hurricane making landfall on or near the Galveston Bay area will cause the surface water to be pushed landward creating up to a 20-25 foot storm surge. In this case, Houston

watersheds could be likely impacted by the combination of storm surge and normal inland flooding due to extreme rainfalls. In the summer of 2005, two devastating hurricanes (Katrina and Rita) made landfall on the Gulf Coast, and caused tremendous damage and loss. Even though very little rain dropped in Houston during Rita, it is vital to evaluate and predict the impact for highly urbanized watersheds based on hydrologic and hydraulic models with water surface elevation data of a storm surge generated by an approaching hurricane. The combination of storm surge data, accurate and updated hydraulic models, and NEXRAD radar within a GIS framework facilitated the discovery of severe inundations in non storm surge zones including major evacuation routes from Galveston (Fang *et al.* 2006). The next generation flood warning system will incorporate storm surge information to better predict the impacts of severe storm on inland watersheds, which will enable emergency personnel to make better-informed decision on likelihood of road-deck inundation on major evacuation routes from Gulf Coast.

Distributed High-resolution Radar Sensing Network (NetRAD)

The accuracy of the current FAS2 can be quite good for regional events over large basins, but lacks for events where regional/local scale interactions, local scale precipitation, infiltration losses, or local hydraulics (storm sewers/urban drainage network) are important. In order to improve the success of FAS predictions for Brays Bayou and TMC and eventually for White Oak and Buffalo Bayous that impact downtown Houston, hydraulic routing, hydrologic mechanisms, and meteorological processes all need to be addressed in the system. In order to do so, both local and regional scale quantitative precipitation forecasts and quantitative precipitation estimates from new and more accurate NetRAD radars (with rainfall data at the scale of a city block) are necessary. Engineering Research Center (ERC) of National Science Foundation (NSF) has funded these systems through Collaborative Adaptive Sensing of the Atmosphere program (CASA) to improve warning lead time and provide timely and accurate forecasts by installing a distributed high-resolution radarsensing network (NetRAD) in Houston, which will cover 60% of the Houston area and greatly improve City's ability to forecast severe events and to direct emergency response at many levels. Figure 2 shows three proposed sites for NetRAD radars: Texas Medical Center, TranStar, and Houston Memorial Hospital. The first NetRAD has been installed on the top of Smith tower, the second tallest building in TMC in November of 2006. Hopefully, it will be operational in March of 2007.

Development of Floodplain Map Library

Current flood warning problems need solutions that use output from more than one type of hydrologic simulation model. For instance, a real-time flood warning system not only requires a hydrologic module to convert rainfall to runoff but also a hydraulic module to route the flow through the stream and predict the water surface elevations in real time. Direct integration of hydrologic and hydraulic models is very difficult (Whiteaker *et al.*, 2006). Since FAS2 has great potential to predict flood in hydraulic perspective in terms of interpreting flow rates into floodplains based on its excellent hydrologic forecasting capability, it is being used as a platform to develop a hydraulic prediction tool – floodplain map library. The linkage of NEXRAD with

improved hydrologic and hydraulic models will provide a major step forward in prediction accuracy for FAS2.

Even though the standardized hydraulic modeling tool (HEC-RAS) designed by the Hydrologic Engineering Center (2002) is able to delineate floodplains when inputting flow rates at corresponding cross sections, it has difficulties in handling large and intense unsteady-state hydraulic computations in real time (Whiteaker *et al.*, 2006). In order to approach the goal of visualizing floodplains under various rainfall intensities and durations when storms progress, a unique series of floodplain maps have to be delineated in advance based on the carefully selected design rainfalls that represent typical rainfall distribution found from a statistical analysis. Since developing the floodplain map library system as a new hydraulic prediction tool is time- and effort-consuming, only some preliminary results for the White Oak watershed are available to show in this paper. The development of floodplain map system for White Oak was accomplished in three major steps:

- A statistical study has been performed to investigate rainfall patterns, durations, and intensities of rainfall events from the past 7 years over the Brays Bayou watershed.
- A matrix of rainfall patterns in terms of durations and intensities were assigned to the upstream and the downstream sections of the watershed to create hydrographs, floodplain maps, and cross-section views for these patterns.
- An algorithm has been designed and is being tested to indicate, based on actual rainfall measurements, which rainfall patterns, floodplain maps, and water surface profiles are most appropriate for the storm as it progresses.

Figure 3 shows the mechanism of floodplain map library system. Based on a statistical analysis of historical rainfall gage data within the White Oak watershed, it is found that designing of 68 series of rainfall patterns with respect to various frequencies (10-yr, 25-yr, and 100-yr), durations (3 hrs, 6 hrs, 9 hrs, 12 hrs, and 24 hrs), and spatial varieties (upstream and downstream) can sufficiently cover all rainfall possibilities over the watershed. Table 1 shows the rainfall depth versus rainfall pattern. It is found that rainfall depth increases with certain patterns of durations. Not only does the floodplain map library system have capability of zooming in certain hotspots and major transportation routes that repeatedly suffer flooding in the past but also it visualizes several cross-section views of critical transportation bridges across the White Oak watershed. This new hydraulic prediction tool with the existing hydrologic prediction feature on the interactive web site will provide the end users with comprehensive understanding of dynamic flood response allowing emergency personnel to quickly determine likely road inundations and begin flood preparations with as much lead time as possible (Fang *et al.*, 2006).

Conclusions

The current flood alert system (FAS2) has been designed to incorporate realtime NEXRAD radar data, GIS, hydrologic models, and the internet for the purpose of providing advanced warning to the Texas Medical Center (TMC) in Brays Bayou located in southwest Houston, Texas. The FAS2 system has been tested on 10-15 storm events with good success since 2003. The following important observations are based on the development and operation of the FAS.

- 1. The current radar-based Flood Alert System (FAS2) can be a good platform to build an enhanced flood alert and control systems for Houston by integrating two TSARP fully studied major watersheds (White Oak and Buffalo Bayou) draining towards downtown Houston, incorporating a distributed CASA high-resolution radar-sensing network (NetRAD) that will provide more accurate on rainfall estimates than NEXRAD.
- 2. TSARP provides updated hydrologic and hydraulic models for each watershed within Harris County. The more accurate cross-sectional data within TSARP models facilitated the development of the floodplain map library, and will be incorporated with storm surge data to increase accuracy of flood forecasting during severe weather.
- 3. The unique floodplain map library system is being integrated to the current system (FAS2) to visualize floodplains under various rainfall intensities and durations when storms progress. This is valuable feature compared to only graphing of hydrologic response. The new system allows allowing emergency personnel to comprehensively understand dynamic responses of the watersheds and to quickly determine likely inundations and begin flood preparations with as much lead time as possible.

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Gallery

Table 1. Rainfall patterns versus total rainfall depths for 10yr, 25yr, and 100yr design rainfall. "U" means rainfall drops at upstream, while "D" means rainfall drops at downstream.

	10 Yr Rainfall	25 Yr Rainfall	100 Yr Rainfall
Rainfall Pattern	Total (cm)	Total (cm)	Total (cm)
U3HR_D3HR	11.98	13.95	17.20
U6HR_D3HR	13.21	15.54	19.31
U3HR_D6HR	13.21	15.54	19.31
U6HR_D6HR	14.44	17.14	21.41
U9HR_D6HR	15.25	18.21	22.83
U6HR_D9HR	15.25	18.21	22.83
U9HR_D9HR	16.05	19.27	24.24
U12HR_D9HR	16.66	20.09	25.35
U9HR_D12HR	16.66	20.09	25.35
U12HR_D12HR	17.28	20.91	26.45
U24HR_D24HR	20.58	25.42	32.55



Figure 1. Rice/TMC flood alert systems (FAS) data input and operational flowchart.







Figure 3. Schematic flow chart for the development of the floodplain map library.