Report for 2005TX193B: Enhancing A Distributed Hydrologic Model for Storm Water Analysis within a GIS Framework in an Urban Area

Publications

- Articles in Refereed Scientific Journals:
  - Bedient, P. B.; A., Holder; J. F., Thompson; Z., Fang, 2006, Modeling of Stormwater Response Under Large Tailwater Conditions for the Texas Medical Center, Journal of Hydrologic Engineering, ASCE. 2006 (Submitted).
- Conference Proceedings:
  - Fang, Z.; E., Safiolea; P. B., Bedient; B. E., Vieux, 2005, Enhanced Flood Alert System for Houston, 2005 National Hydrologic Warning Council Conference: Flood Warning Systems, Technologies and Preparedness. Sacramento, California, May 16-20, 2005.
  - Fang, Z.; P. B., Bedient; R., Hovinga, 2006, Prediction of Severe Storm Flood Levels for Houston Using Hurricane Induced Storm Surge Models in GIS Frame, American Water Resource Association 2006 Spring Specialty Conference: GIS and Water Resources IV, Houston, Texas, May 8-10, 2006.
  - Fang, Z.; E., Safiolea; P. B., Bedient, 2006, Enhanced Flood Alert and Control Systems for Houston, “Proceedings of 25th American Institute of Hydrology Conference: Challenges of Coastal Hydrology and Water Quality”, Baton Rouge, Louisiana, May 21-24, 2006.

Report Follows

Enhancing a Distributed Hydrologic Model: Addition of Storm Water Pipe Analysis within a GIS Framework in an Urban Area

Zheng Fang

Abstract

The City of Houston has been facing flood problems of a serious nature, some of which occurred in 1989, 1992, 1994, 1998, 2001, and 2003. Tropical Storm Allison in June 2001 created the most extensive urban flood damage in U.S. history ($5 billion). Urban flood problems have repeatedly brought attention to the need for improved urban drainage design and flood prediction, as in the case of the Texas Medical Center flooding in 2001. In order to improve flood alert capabilities for highly urbanized areas with dense drainage systems, the physics-based distributed model, VfloTM, was chosen because it preserves the spatial variability by dividing the model domain into small, interconnected cells to better represent watershed features. VfloTM has been tested with a number of rainfall events that affected the Houston area from 1998 to 2003. Incorporation of NEXRAD radar rainfall data, GIS databases, and detailed storm water system data with enhanced distributed hydrologic modeling tool (VfloTM) enables us to develop an advanced storm water modeling system in highly urbanized Harris Gully area to provide decision makers of TMC with more accurate flooding warning information in order to initiate timely evacuation plans under severe weather conditions. The original VfloTM model represented this network as overland flow model elements with only a short, trapezoidal channel reach draining into Brays Bayou. An updated hydrologic model for Harris Gully has been set up by feeding both higher spatial and temporal resolution precipitation data into an enhanced distributed hydrologic model of the same spatial resolution that more fully represents the storm water drainage network for Harris Gully. In the updated model, a much more extensive representation of the actual drainage network has been used by including channels to represent the sewer and road systems within the basin. Using channel elements to simulate overland flow along the road and sewer network has typically resulted in a better fit with respect to peak discharge magnitude and timing. It has been carefully calibrated against 6 historical rainfall events. This innovative flood modeling system will provide more accurate data on problematic flow areas in storm sewer systems and associated watersheds. The increased information and accuracy of flood levels will provide TMC decision-makers with more accurate flood warning information, enabling them to initiate timely evacuation plans under severe weather conditions. In addition, it will build a solid foundation for a future real-time flood alert system for areas as small as Harris Gully.

Introduction

Flooding is considered the number one natural disaster in the United States in terms of damage cost. According to the National Oceanic and Atmospheric Administration and National Climatic Data Center data for the period between 1980 and 2004, 28 out of 60 disasters that occurred in the 1990s were directly flood related (NCDC, 2004). Today the average for flood damage costs in the United States has risen to over $4 billion annually (NWF, 1998). 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. This indicates the severity of the flood problem at the national level, even after the years of investment in flood control (Bedient and Huber, 2002).

The City of Houston has been facing flood problems of a serious nature, some of which occurred in 1989, 1992, 1994, 1998, 2001, and 2003. Ninety percent of Houston rainfall events are convective storm systems (Schwertz, personal communication, 1998). Typical summer convective storms are extremely variable in space and time (Schell et al., 1992) and can produce very intense rainfall rates that lead to localized flooding (Doswell et al., 1997).

Harris Gully watershed, a subwatershed of Brays Bayou, drains approximately 14.2 km2 (5.5 mi2) and flows in large box-culverts underneath the Texas Medical Center (Figure 1). The TMC was extensively flooded during TS Allison in June of 2001; storm water in Harris Gully overflowed, causing flooding of the streets and buildings around the TMC. This flooding was due to high urbanization, flat slope, clayed-soil characteristics, and backwater effects at the downstream of Harris Gully caused by high flows in Brays Bayou, and it resulted in millions of dollars in damages. The hydrology and hydraulics of Harris Gully are complex due to large channelization into conduits below street level, particularly in its lower reaches directly underneath the TMC. In order to improve flood forecasts further for the TMC, we focused on development of an enhanced distributed hydrologic model for Harris Gully that better represents the storm water drainage network than the existing one does.

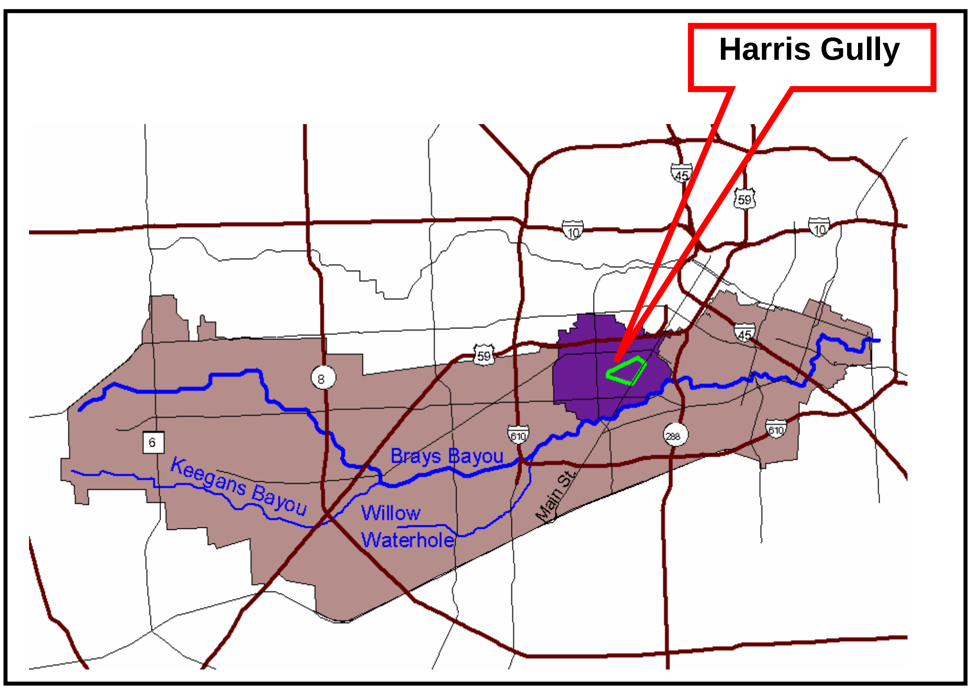

Figure 1: Brays Bayou (334 km2), and Harris Gully (purple shading 20.7 km2)

The availability of NEXRAD radar data, GIS databases, accurate distributed hydrologic modeling tools, and detailed storm water system data has made the development of advanced storm water modeling systems possible. Incorporation of NEXRAD radar rainfall data, GIS databases, and detailed storm water system data with enhanced distributed hydrologic modeling tool (VfloTM) enables us to develop an advanced storm water modeling system in highly urbanized Harris Gully area to provide TMC decision-makers with more accurate flooding warning information, enabling them to initiate timely evacuation plans under severe weather conditions.

Research Needs

Urban flood problems have repeatedly brought attention to the need for improved urban drainage design and flood prediction, as in the case of the Texas Medical Center (Vieux and Bedient, 2004) after the Tropical Storm Allison flood of June, 2001. This flood was reported by the National Oceanic and Atmospheric Administration as the most damaging urban flood in U.S. history, dropping nearly 15.2 inches of rainfall in three hours over much of the lower section of Brays Bayou and downtown Houston. An estimated $5 billion in damages and about 50,000 damaged structures were reported throughout Harris County. The TMC alone accounted for nearly $1.5 billion in damages resulting from flooding in Harris Gully near Brays Bayou. Until more permanent solutions are found, it is vital to develop real-time hydrologic models as platforms for early warning flood systems to provide the warnings that public and private entities are demanding. Modeling of both storm water pipes and overland flow in an urban system can produce more accurate runoff hydrographs at various points in the watershed. This would provide emergency personnel with more useful information to determine exact locations of flood- prone areas and design deficiencies, especially in highly-urbanized settings. However, one of the critical problems is that storm water sewer systems (pipes) are generally not modeled as part of hydrologic flood analyses for urban watershed areas. Although the Storm Water Management Model (SWMM) developed by the EPA is capable of simulating storm water pipes, it is difficult to handle overland flow and distributed data such as rainfall radar data and Light Detection And Ranging (LiDAR) data. Furthermore, SWMM cannot run easily in real time, which is an obstacle for future development of real-time flood warning systems. Therefore, we enhanced an existing distributed hydrologic model (VfloTM) for overland flow by adding in the ability to analyze the storm water system of pipes.

The primary objective of the research was to achieve more accurate and timely flood forecasts for Harris Gully area by adding pipe flow effects into an existing hydrologic distributed model (VfloTM) in a GIS framework and by using pre-calibrated NEXRAD radar rainfall data for 6 historical events.

Methodology

Distributed Hydrologic Model (VfloTM)

Currently, two general classes of models are available; they are classified as lumped or distributed depending on how the model handles spatial variability (Vieux et al., 2002). In this research, the physics-based distributed model with a commercially available hydrologic modeling package (VfloTM) developed by Vieux & Associates, Inc. has been chosen to simulate runoff from radar rainfall input. Because lumped models such as HMS are limited by their failure to account for small-scale variations of the hydrologic processes (Muzik, 1996), VfloTM is used to solve the kinematic wave method for both overland and channel flood routing in a finite element mesh. Distributed models preserve spatial variability by dividing the model domain into small, interconnected cells, which makes them suitable for distributed hydrologic forecasting to better represent watershed features. VfloTM has been tested by a number of rainfall events that affected the Houston area from 1998 to 2003 (Bedient et al., 2003). Stewart (2003) built the first distributed hydrologic model using radar rainfall data on Brays Bayou watershed in Houston, Texas. Moreover, Safiolea and Bedient (2004) applied VfloTM to address land use and subsidence impacts on the White Oak Bayou watershed northwest of Houston.

NEXRAD

Given the extremes that can occur in spatial and temporal rainfall variability in the Texas Gulf Coast region, it is difficult to detect floods at the watershed level with sparsely placed rain gauges. A study by Johnson and Dallman (1987) found that rain gauges have limited ability to detect rainfall with enough response time, which is needed for flood prediction and warning. However, the availability of the new WSR-88D (NEXRAD) weather radar for use in rainfall estimation and flood prediction greatly improves the spatial and temporal coverage of a watershed for prediction purposes. Smith et al. (1996) and Johnson et al. (1999) both examined the contrasting detection capabilities of the NEXRAD and rain gauge networks. WSR-88D or Next Generation Radar Rainfall (NEXRAD) radar allows for the tracking of storms in space and time up to 230 km away from a radar installation. The central Houston area is located approximately 45 km from KHGX radar installation, an optimum distance for the hydrologic application of radar rainfall data (Crum et al., 1993). The system proved its worth when applied to rapidly responding highly urbanized watersheds such as Brays Bayou, where the NEXRAD/GIS-based system allowed for more accurate flood prediction than could have been possible using more traditional monitoring approaches. Therefore, calibrated radar rainfall data for historical rainfall events from NEXRAD were chosen to feed into the updated hydrologic model due to its higher accuracy.

GIS

A hydrologic analysis using spatially-oriented radar data, defined watershed boundaries, and other spatial hydrologic parameters is greatly enhanced by the use of GIS. The linkage of NEXRAD and a GIS system makes estimation of rainfall that has fallen over a specific watershed area feasible. These rainfall estimates can create a powerful system for storm prediction and flood alerts using distributed-parameter models (VfloTM) (Vieux, 2001).

LiDAR

Distributed models depend on accurate descriptions of the drainage network. Elements of the drainage network such as slope, flowpath, and drainage density are usually derived from a raster digital elevation model (DEM). DEMs are utilized in delineating watershed boundaries to yield more accurate hydrologic basin models than traditional approaches. In this research, the database developed by Harris County LiDAR released in 2002 was used as input to the application area for the model.

The availability of NEXRAD radar data, GIS databases, accurate distributed hydrologic modeling tools, and detailed storm water system data has made the development of advanced storm water modeling systems possible. Since late 2003, the distributed hydrologic model has been used with RTHEC-1 as an ensemble for real-time flood alert systems (FAS2) for Brays Bayou and Texas Medical Center (TMC). Moreover, it has been applied to address land use and subsidence impacts on White Oak watershed northwest of Houston. Incorporation of NEXRAD radar rainfall data, GIS databases, and detailed storm water system data with enhanced distributed hydrologic modeling tool (VfloTM) enables us to develop an advanced storm water modeling system in the highly- urbanized Harris Gully area to provide TMC decision-makers with more accurate flooding warning information enabling to initiate timely evacuation plans under severe weather conditions.

Developing a new element of stormwater pipe system in the commercial modeling package (VfloTM) and embedding the very dense drainage systems (sewers and streets) within Harris Gully into the existing distributed hydrologic model are very complex processes. Since it is time- and effort-consuming to develop stormwater pipe element alone in VfloTM., the existing channel elements within VfloTM have been converted into stormwater pipe elements with minimum adjustments at this point to enhance the existing distributed hydrologic model for Harris Gully.

The primary focus of the research was to set up an improved hydrologic model for Harris Gully by feeding both higher spatial and temporal resolution precipitation data into a distributed model of the same spatial resolution that more fully represents the storm water drainage network for Harris Gully. The Harris Gully drainage network consists entirely of a series of buried pipes and box-culverts. The original VfloTM model represented this network as overland flow model elements with only a short, trapezoidal channel reach draining into Brays Bayou. In the updated model, a much more extensive representation of the actual drainage network has been used by including channels to represent the sewer and road systems within the basin (Figure 2). Using channel elements to simulate overland flow along the road and sewer network has typically resulted in a better fit with respect to peak discharge magnitude and timing. This improved distributed hydrologic model has been carefully calibrated against 6 historical rainfall events.

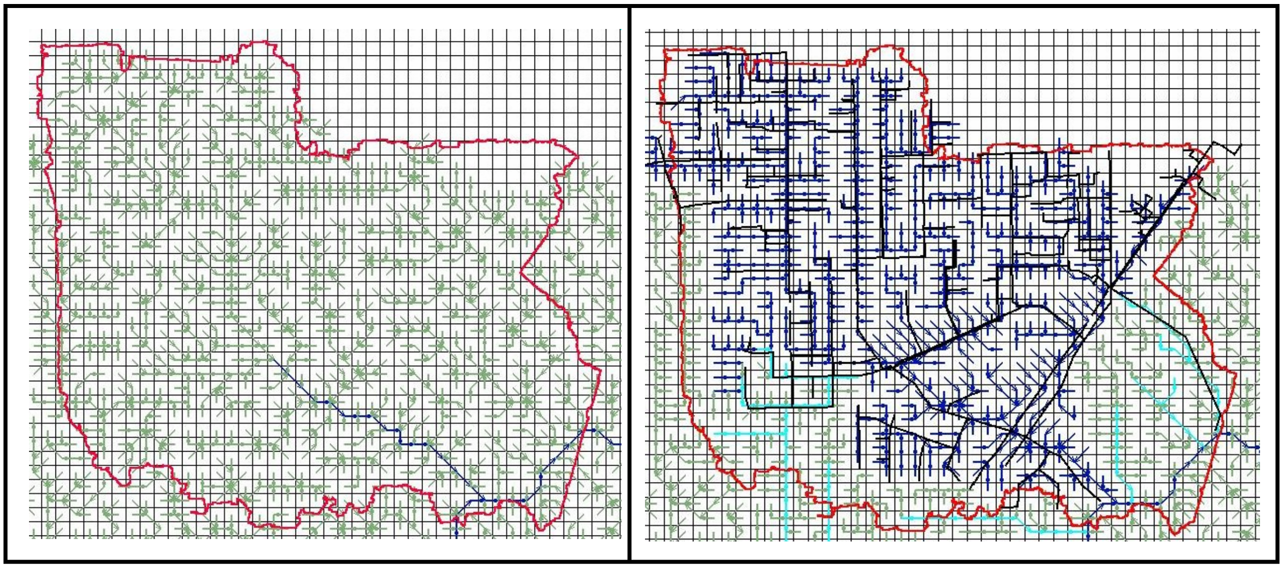

Figure 2 VfloTM Finite Element grid for (a) “Original” Harris Gully Model, a single short box culvert (left); (b)“Improved” Model, an extensive representation of the actual sewer and street network (right)

Results

Several sensitivity analyses have been performed to compare simulation results from the existing distributed model and the improved model. Firstly both models were fed a 24-hour 100-year design rainfall; simulation results from both models for this design event indicate that the improved VfloTM model of Harris Gully is more sensitive to rainfall than the existing model (**Figure 3**).

Secondly, VfloTM model results for T.S. Frances from four combinations of precipitation data and model setup were compared to the observed stage and flow data. Table 1 summarizes the different model runs and provides some comparative statistics describing the results. Results from this table indicate that local rain gage data (HG400) are higher than total rainfall estimated from NEXRAD radar for T.S. Frances. Therefore the runoff depth value from the same model (either original or improved model) using rain gage data is always higher than that from the model using radar rainfall data. Peak runoff values from the improved model generally produced fewer errors than the original did. Additionally, the improved model produced fewer timing errors than the original model did.

Figure 4 depicts modeling results for the August 2002 event with four hydrographs: the flow calculated from the observed stage data recorded in the Harris Gully culvert, the flow modeled using the improved model (solid black line), the flow modeled using a bias correction factor applied to the radar precipitation data of 1.06 (calculated by Baxter Vieux) (dashed blue line), and the flow modeled using the original model (green line). The improved VfloTM model better captures the magnitude of the runoff peak as well as the shape of the first hydrograph rise. The peak, however, is still underestimated, perhaps due to backwater effects which are not accounted for.

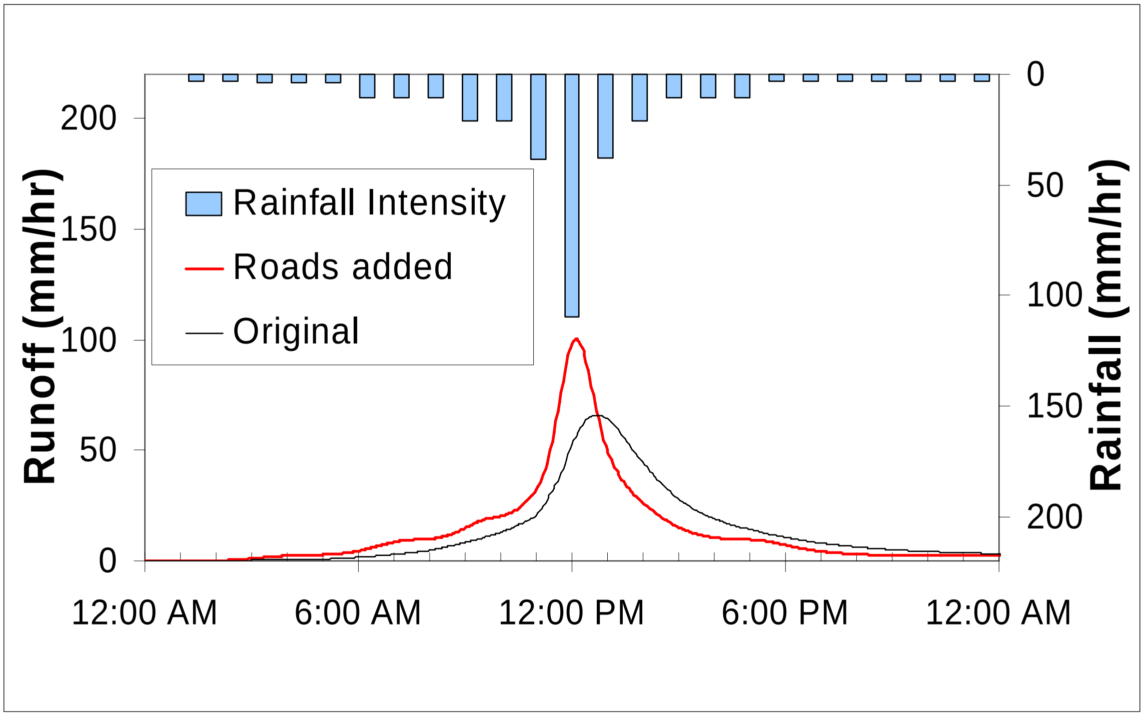

Figure 3 Sensitivity Analysis of VfloTM existing model and upgraded model for Harris Gully

Table 1: Summary of TS Frances modeling runs

Run No.	Rainfall source & (Total (mm))	VfloTM model	Runoff depth (mm) up to 11:24 (error in parenthesis)	Peak runoff error (%)	Timing error to 7ft
1	HG 400 (239.5)	Original	87.6 (-5.2)	-10.3	4 hr 47 mins
2	NEXRAD (218)	Original	73.1 (-20.9)	-4.5	3 hr 55 mins
3	HG 400 (239.5)	Improved	97.2 (+5.2)	5.57	27 mins
4	NEXRAD (213)	Improved	85.1 (-7.9)	4.57	1 hr 14 mins

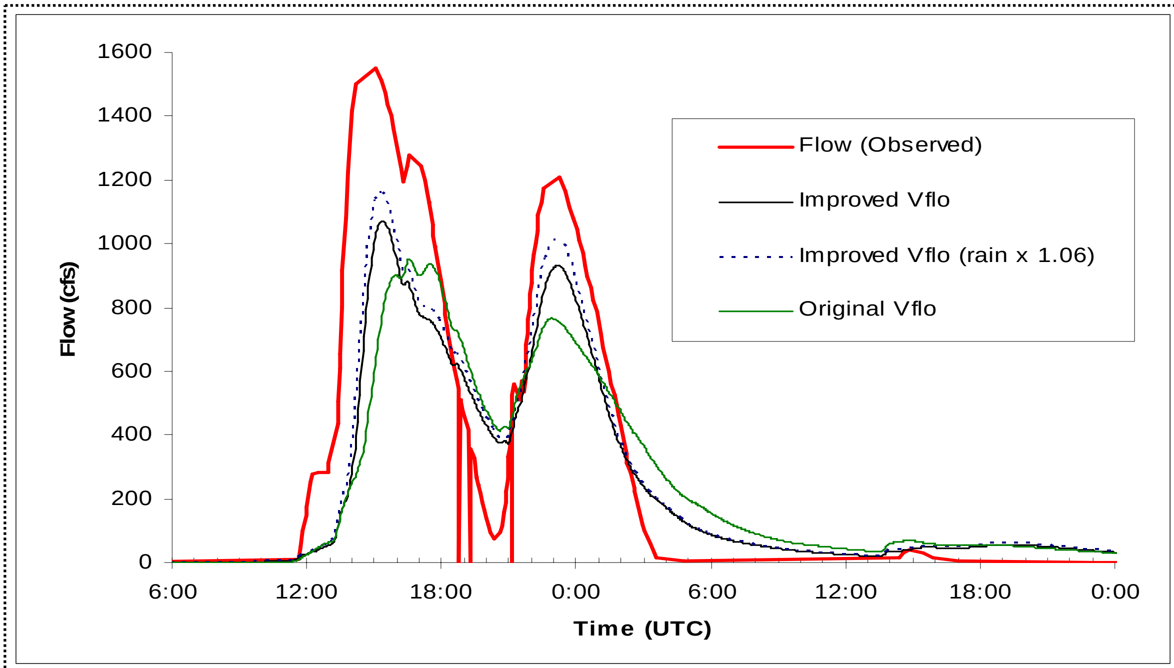

Figure 4 Modeling Results for Harris Gully in August 2002 Event

Conclusions

This research helps us better understand the hydrologic and the hydraulic response of Harris Gully relative to Brays Bayou under severe weather conditions. Finer grid resolution of the enhanced distributed model that fully accounts for Harris Gully with similar resolution radar rainfall data as input can improve flood forecasting capabilities in terms of timing, duration, peak flow, and volume. Six historical rainfall events were used to calibrate the enhanced distributed model.

It has been found that using channel elements to simulate overland flow along the road and sewer network typically results in a better fit with respect to peak discharge magnitude and timing. However, for some events peak flows are still underestimated, likely due to a combination of backwater and surcharge effects not currently accounted for.

Modeling both the storm water pipes and overland flow in an urban system produces more accurate runoff hydrographs at various points in the watershed based on characteristics of distributed models. This modeling can provide emergency personnel with more useful information to determine exact locations of flood-prone areas and design deficiencies, especially in highly urbanized settings.

Because the enhanced distributed hydrologic model provides more accurate flood warning information than the existing model, the results of this research can be grafted into the advanced flood alert system for the TMC with better understanding of the dynamic response of Harris Gully and more accurate flood forecasting capabilities.

Based on more timely and accurate information from this enhanced distributed hydrologic model for Harris Gully, TMC decision-makers are capable of initiating a better evacuation plan. Results from this research are going to ease hundreds of thousands of patients and their relatives in the TMC and even saves their lives. Furthermore, damages caused by flooding within Harris Gully area can be economically diminished to the minimum due to more preparations done during the longer lead-time given by this enhanced distributed model and due to finer resolution certainties of floodplain delineation.

Even though Harris Gully was initially chosen as our research test bed, the technologies and methodology used in this research can be beneficially applied to any coastal areas which are frequently impacted by severe rainfall events and tropical hurricanes.

Future Work

Firstly, a new VfloTM model of this smaller subcatchment will be developed based on a finer grid resolution than the current Brays Bayou model (122m×122m grids). Results from the Harris Gully stand-alone model will be compared with those from an existing urban hydrologic model, for example SWMM. Secondly, simple modifications are going to be made to the model so that it can simulate some of the features typically found in urban areas. These include buried channels (which become drainage culverts) and an anthropogenic drainage network consisting of ditches, manholes, etc. to route the runoff into the subsurface drains (as opposed to a “natural” drainage network where overland flow is routed uniformly across the ground surface into a channel element).

The sensitivity of the modeled (VfloTM) runoff hydrographs to these two-staged changes will be investigated, and the benefits of each stage in terms of the improvement in the model predictions will be quantified. In addition, model accuracy for storms with different characteristics such as duration and direction of movement with respect to the watershed will be investigated. It is hoped that the staged improvements will help the model to accurately forecast moderate (in addition to extreme) hydrologic events that are more sensitive to spatial and temporal variations in precipitation rate, antecedent soil conditions, and the explicit representation of the urban drainage network.

Additionally, Harris Gully area is frequently influenced by the backwater effects caused by high flows of Brays Bayou and severe coastal hurricane surges, which causes the storm water pipe system to be under the pressured flow circumstances that VfloTM cannot address precisely. However, updated hydrologic models provided by TSARP for Harris Gully, when incorporated with HEC-RAS, could generally account for the backwater issue and delineate floodplains in local scale under storm surge scenarios

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