Real-time urban runoff simulation using radar rainfall and physics-based distributed modeling for site-specific forecasts

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ABSTRACT

Quantitative precipitation estimates (QPE) derived from radar are useful in runoff simulation in urban drainage. Simulation experiments using radar data sampled at various resolutions identify the limits to predictability for various basin sizes. Spatial resolution of radar rainfall used as input to a distributed model affects prediction error and scales with drainage area. Radar data used in this analysis are derived from both S-band (NEXRAD) and X-band radars. Using radar QPE derived from the existing WSR-88D (KHGX) as input to a physics-based hydrologic model of Brays Bayou (260 km^2) provides a baseline for comparison and guides design of future radar networks. Results of experiments using historical radar events, including the tropical storm Allison, indicate that accurate rainfall-runoff predictions in real-time are possible and useful for site-specific forecasts. Radar and distributed hydrologic model provide accurate rainfall and runoff data supporting site-specific flood information.

KEYWORDS

Urban drainage; stormwater; flooding; radar; distributed hydrologic modelling; GIS.

INTRODUCTION

Stormwater runoff significantly impacts flooding and water quality in urban areas. Advances in stormwater runoff modeling, as well as in radar technology for the detection and forecasting of complex precipitation patterns, help to characterize the performance of urban drainage infrastructure at both regional and local scales. Customized flood forecasting depends on three subsystems to support real-time operations. The three subsystems described in this paper consist of 1) monitoring current rainfall, 2) projecting future rainfall, and 3) distributed runoff prediction of flow levels in the main channel of Brays Bayou. Recent revisions to the Flood Alert System (FAS) have made several improvements including the operation of both a lumped and physics-based distributed model providing ensemble operational forecasts in Brays Bayou for the TMC.

Customized Flood Forecasting

Advances in technology such as real-time radar rainfall, automatic stream gage systems, and automated data reporting dissemination via the Internet have made it possible to develop and operate customized site-specific warning systems. Operational deployment of radar-based distributed flood forecasting systems rely on multisensor quantitative precipitation estimates (QPE) that use radar and gauge rainfall rates as input (Vieux et al., 2003) whereas historically, operational flood forecasting relied on using lumped conceptual models. A customized operational flood forecasting system that provides critical information to the Texas Medical Center (TMC) in Houston is the Rice University/TMC Flood Alert System (www.floodalert.org). The TMC is the largest medical center in the world covering a 2.8-km^2 campus with 42 member institutions that include 13 hospitals. Over 62,000 people are employed in these facilities. Imminent flooding in Brays Bayou adjacent to the medical center dictates that specific actions be taken that include placing member institutions on alert, closing floodgates, or suspending patient care and evacuating the hospitals/facilities. The forecast point of interest to the TMC is located at Main Street just upstream where it crosses Brays Bayou. Tropical Storm (TS) Allison caused the shutdown of the TMC in 2001, whereas a shut down was narrowly averted during TS Francis in 1998. Information derived from the TMC-customized system supports operations and logistical measures designed to reduce flood losses, and further details on the system may be found in Bedient et al. (2000); Bedient et al. (2002); and Bedient et al. (2003).

Flooding Concerns in Urban Areas

The TMC can be impacted by either of two flood production mechanisms common in urban areas, regional- and local-scale flooding, caused by the main channel of Brays Bayou and local drainage from Harris Gully, which interacts with Brays Bayou. Localized flooding, also called nuisance flooding, occurs where stormwater inlet capacity is exceeded by runoff resulting from intense and often short-lived rainfall. Regional flooding is the consequence of rainfall-runoff accumulating from watershed areas that are developed, undeveloped, or of mixed land use. The interaction between these scales occurs in low gradient topography where backwater from channels conveying regional-scale runoff reduces the efficiency of local culverts draining smaller-scale areas. Otherwise, the two processes are independent with local runoff feeding forward to the regional-scale runoff without feedback. The time scales of these two processes may or may not coincide depending on the distribution of rainfall over the regional scale watershed and localized intense cells embedded in the larger-scale precipitation producing atmospheric conditions. Examples are convective cells embedded within a tropical storm, or intense stormcells embedded in frontal precipitation feature. The network of local drainage infrastructure (small watersheds) embedded in the regional scale watershed is a significant challenge to both the analysis of such systems and the prediction of the hydrologic response. The complex interaction of input with drainage infrastructure presents challenges to the design of stormwater drainage infrastructure, the management of flooding, flood mitigation, and real-time forecasting of multi-scale urban drainage systems with multi-scale inputs.

Real Time Predictions

Making predictions in real-time with a hydraulic model is difficult because of inaccuracies in model parameters, rainfall input inaccuracy, or unknown upstream flow rates. Real-time systems for mapping expected areas of inundation require input of flow rates from another source to generate inundated areas using sophisticated 2-D hydrodynamic models. Even the inflow between river gauging stations requires some model estimation of watershed response in the intervening areas. Upstream gauging points and rainfall-runoff models are viable sources of real-time flow information. Both lumped and physics-based distributed rainfall-runoff models may be used for this purpose.

Distributed hydrologic modeling relies on geospatial data used to define topography, landuse/cover, soils, and precipitation input. Distributed hydrologic modeling may be termed physics-based if it uses conservation of momentum, mass and energy to model the processes. Solution of flow analogies (e.g. kinematic, diffusive wave, or full dynamic) employs numerical methods with a discrete representation of the catchment as a finite difference or finite element grids. Example models, termed physics-based or physically-based distributed models (PBD), include *r.water.fea*; a parallel version of *r.water.fea* called the distributed hydrologic model (DHM); V*flo*™ distributed hydrologic model (Vieux and Vieux, 2002; and Vieux et al. 2003). The digital revolution in geospatial data has helped develop and make physics-based modeling practical.

Radar Capabilities

Radar capability to provide accurate rainfall estimates over large areas at high resolution has the potential to provide needed rainfall inputs to models for inundation forecasts and custom flood alert systems. The WSR-88D radar deployed in the US by the US National Weather Service (NWS) is a 10-cm wavelength (S-band) radar. It is designed for long-distance surveillance given the ability of 10-cm wavelengths to penetrate rainfall with little attenuation. With a 10-cm wavelength, under most conditions, the useful range is considered to be 180 km or less. The NEXRAD precipitation processing algorithm employed by the NWS produces precipitation estimates out to 230 km. As distance increases, the beam measures higher above average ground level (AGL) because of the angle of the first tilt beam, which is 0.5 degree. At 180 km, the beam is 3.5 km AGL and may overshoot low clouds. Additional details on hydrologic applications of radar, and its characteristics related to precipitation measurements, may be found in Einfalt et al. (2004).

The radar beam overshoot at long distances of 10-cm wavelength radars results in undersampling of the atmosphere below several kilometers. In areas of warm-process precipitation generation low in the atmosphere, the overshoot can lead to underestimation of the rainfall. To overcome this limitation, a new radar system is being developed called NetRAD composed of X-band radars that will sample lower in the atmosphere than NEXRAD radars. Lower tilt elevations are possible because of the lower peak beam power than NEXRAD. Figure 1 shows planned configuration of X-band radars that will cover the Brays Bayou watershed. The Collaborative Adaptive Sensing of the Atmosphere (CASA) Engineering Research Center is undertaking development and deployment of this system to accomplish enhanced precipitation estimation for purposes of detecting flood producing rainfall and other severe weather hazards such as tornadoes.

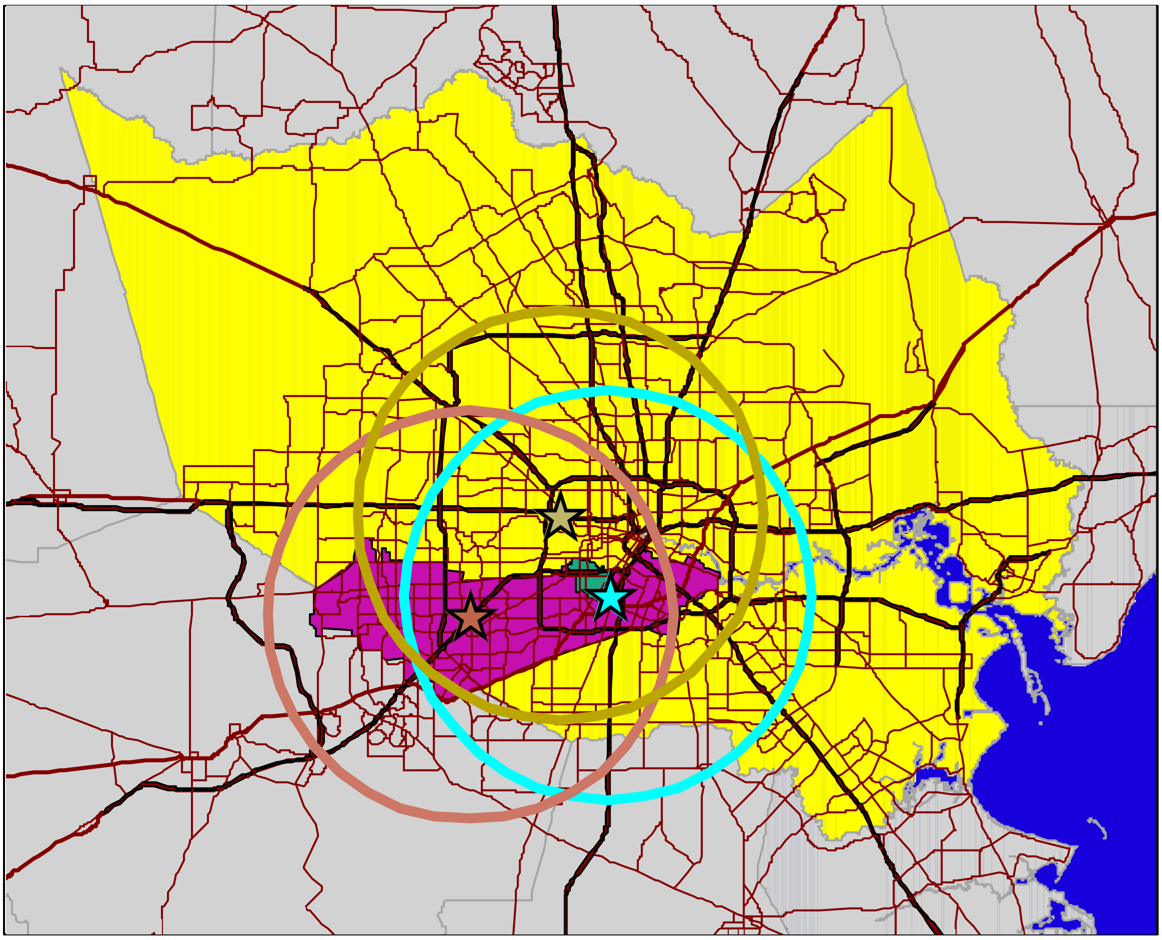

Figure 1. Location of Brays Bayou in Houston and Harris Counties in relation to planned X-band radars.

Real-Time Radar Rainfall

Gauge adjusted radar rainfall provides high-resolution input to the modeling subsystem in real-time. The system uses NWS radar data (Level 2) from the nearby NEXRAD radar (KHGX) located approximately 50 km away. Radar data accuracy is enhanced using rain gauge data in real-time to provide high-precision radar rainfall for quantitative hydrologic applications. Figure 2 shows the 1-degree by 1-km spatial resolution of the data over Harris Gully contained within Brays Bayou. The main channel of Brays Bayou flows from southwest in an easterly direction in the lower right portion of the aerial photograph.

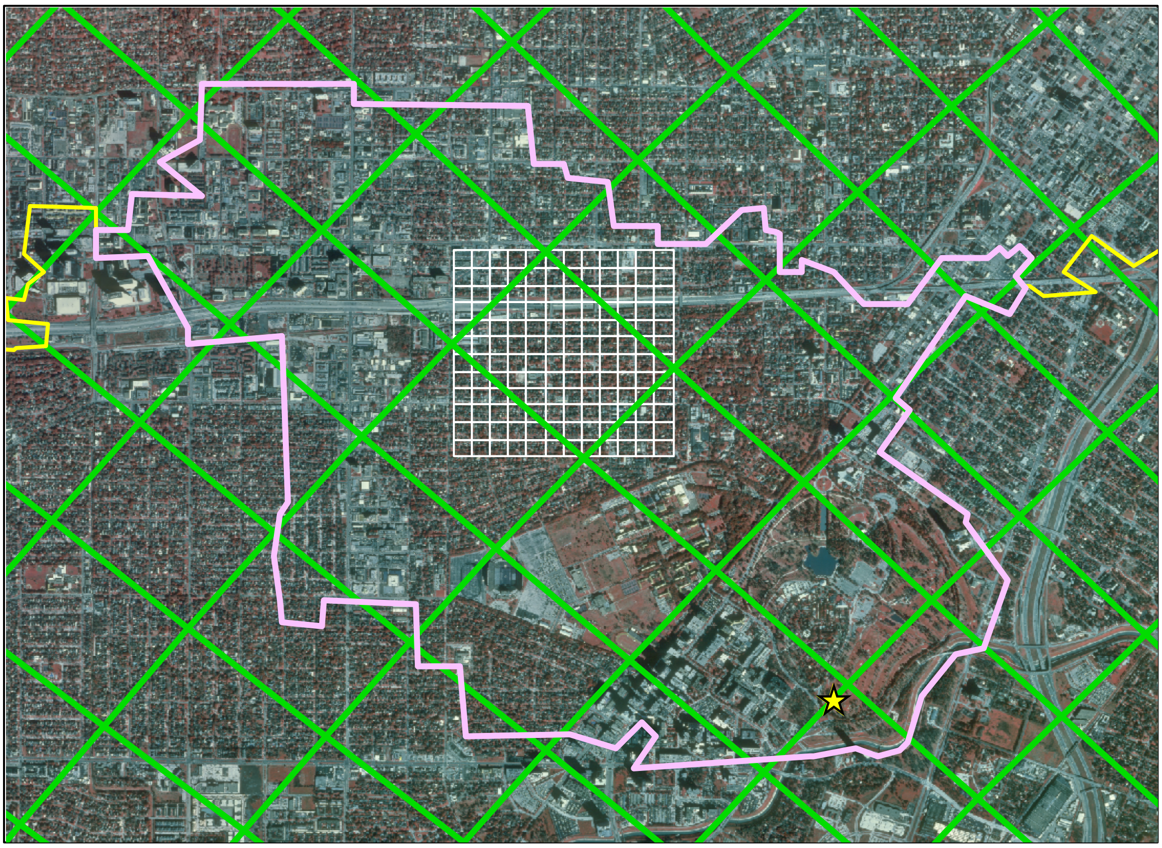

Figure 2. Radar sample volume resolution over Harris Gully. The large grid is the 1 x 1 km radar grid from the NEXRAD radar. The high-resolution inset is at 100-meter resolution representative of X-band radar resolutions. The TMC is seen in the photograph at the bottom center indicated by the star, which is the discharge location of the box culverts draining Harris Gully.

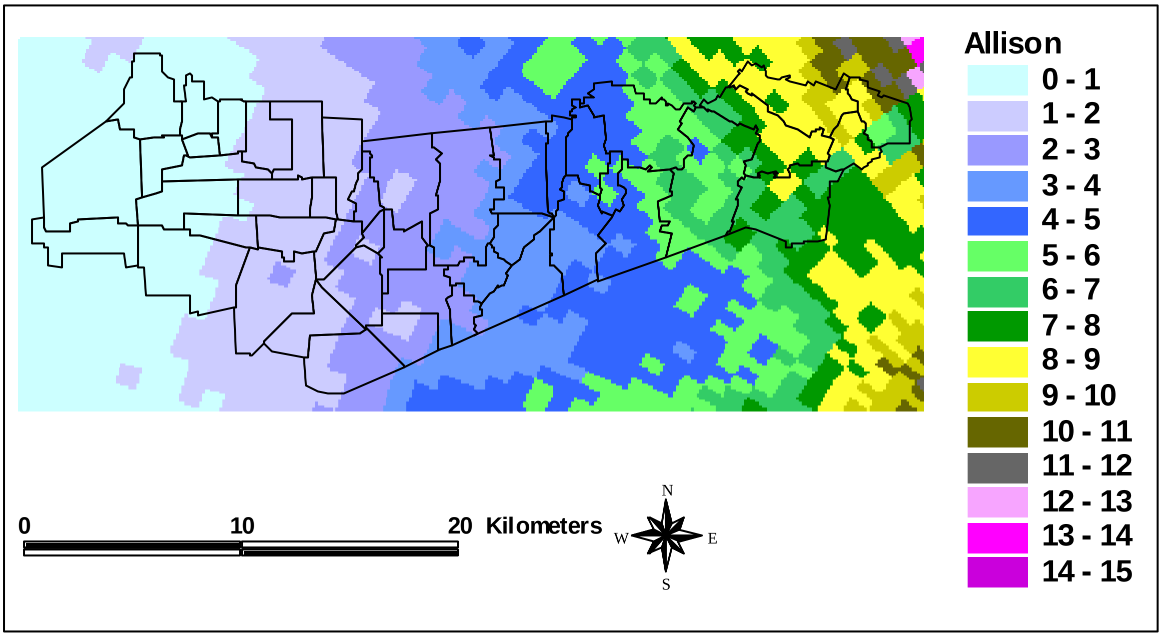

Figure 3. Rainfall event total map over Brays Bayou for Tropical Allison on June 5, 2001.

Display of this information is important for emergency management decision making. Figure 4 shows the real-time rainfall-runoff monitoring web page used to display rainfall and runoff over the watershed.

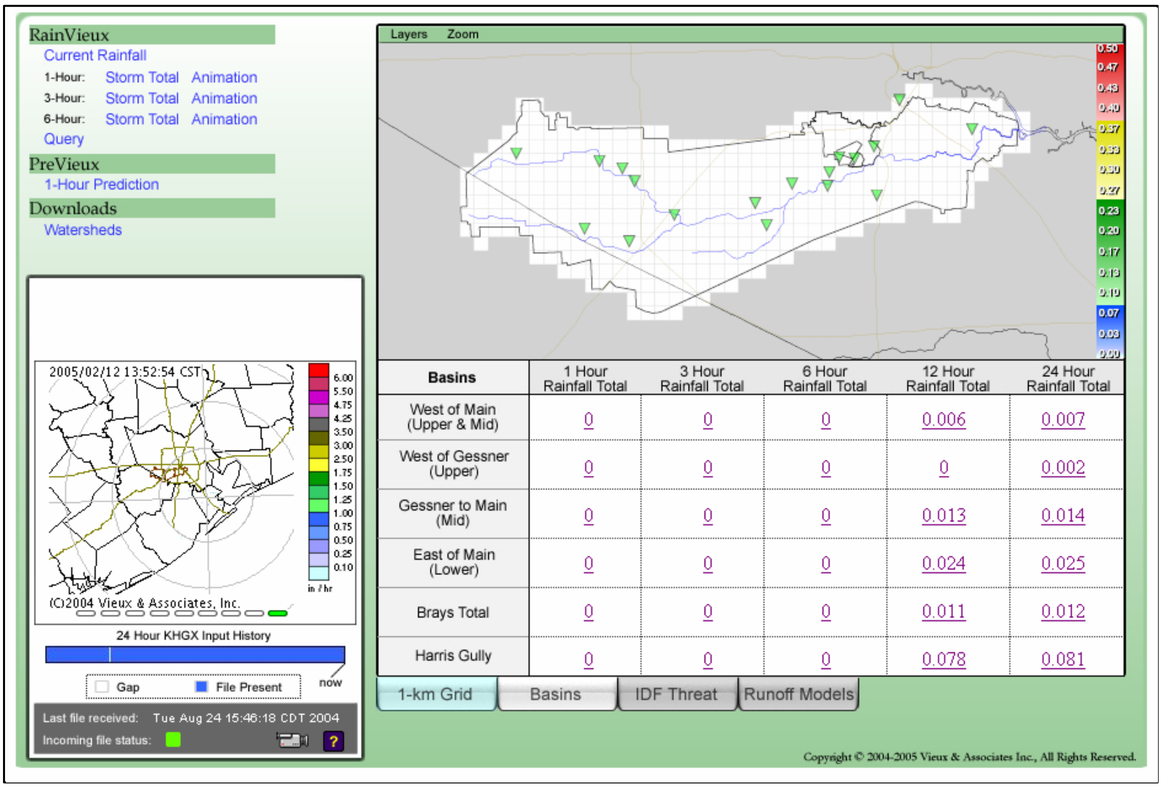

Figure 4. Web page for rainfall and runoff display with map features, stream and rain gauges. Rainfall totals, animations and a regional display shows approaching rainfall.

Data display options include radar bin resolution and aggregated basin averages as requested. Several options exist for the display of areas exceeding a pre-defined rainfall threshold and display of runoff from the model ensemble.

Real-time hydrologic prediction

Real-time runoff prediction using radar and rain gauge input is supported with V*flo*™, a fully distributed, physics-based hydrologic model capable of utilizing geographic information and multi-sensor precipitation input to simulate rainfall runoff from rural and urban catchments. Model setup and is based on terrain, land cover and impervious areas, and channel hydraulics. Figure 5 shows an example of GIS data used to setup the model. Hydraulic roughness shown here from V*flo*™ is derived from 30-m Land Sat according to the dominant land use/cover classification (Vieux, 2005).

The characteristics of Brays Bayou and modeling studies have been reported by Vieux and Bedient (2004). The basin has a drainage area of 260 km^2 at the Main Street gauge operated by the USGS. At low flows (<4 m^3/s), stages are influenced by tidal fluctuations, which is the meaning of the term "bayou". The region is highly urbanized with about 85% of the watershed developed. The lower 42 km of channel is concrete lined with a trapezoidal cross-section that has a 15-m bottom width and 3:1 side slopes in the downstream areas including near Main Street. Extending to the headwaters, channel bottom widths decrease to ~5 m with the same 3:1 side slopes. Slopes in overland and channel areas are quite flat ranging from a maximum of 4.96% to a minimum of 0.001% downstream of Main Street to the East. Channel slopes above Main Street are generally 0.055% or flatter with upstream channel slopes in the headwaters around 0.2%. For additional details, see Vieux and Bedient (2004); Bedient et al. (2003); Bedient et al. (2000, 2003); and Holder et al. (2002). Runoff model ensemble estimates are provided by both HEC-1 and the physics-based model V*flo*™, which after setup, calibration, and validation is operated in real-time. Through event reconstruction, Vieux and Bedient (2004) found that the achievable model accuracy is approximately 11.8% in peak discharge, 12 min in timing, and 11.1% in runoff volume at the Main Street gauge with a drainage area of 260 km^2. Figure 5 shows the finite element network representing the drainage direction defined by LiDAR topographic elevations. The hydrograph is shown for an event that occurred in July 24-25, 2003. The accuracy of the event shown was achieved in post-analysis after controlling for radar bias. To enhance prediction accuracy in real-time, radar bias correction will be achieved using real-time gauges.

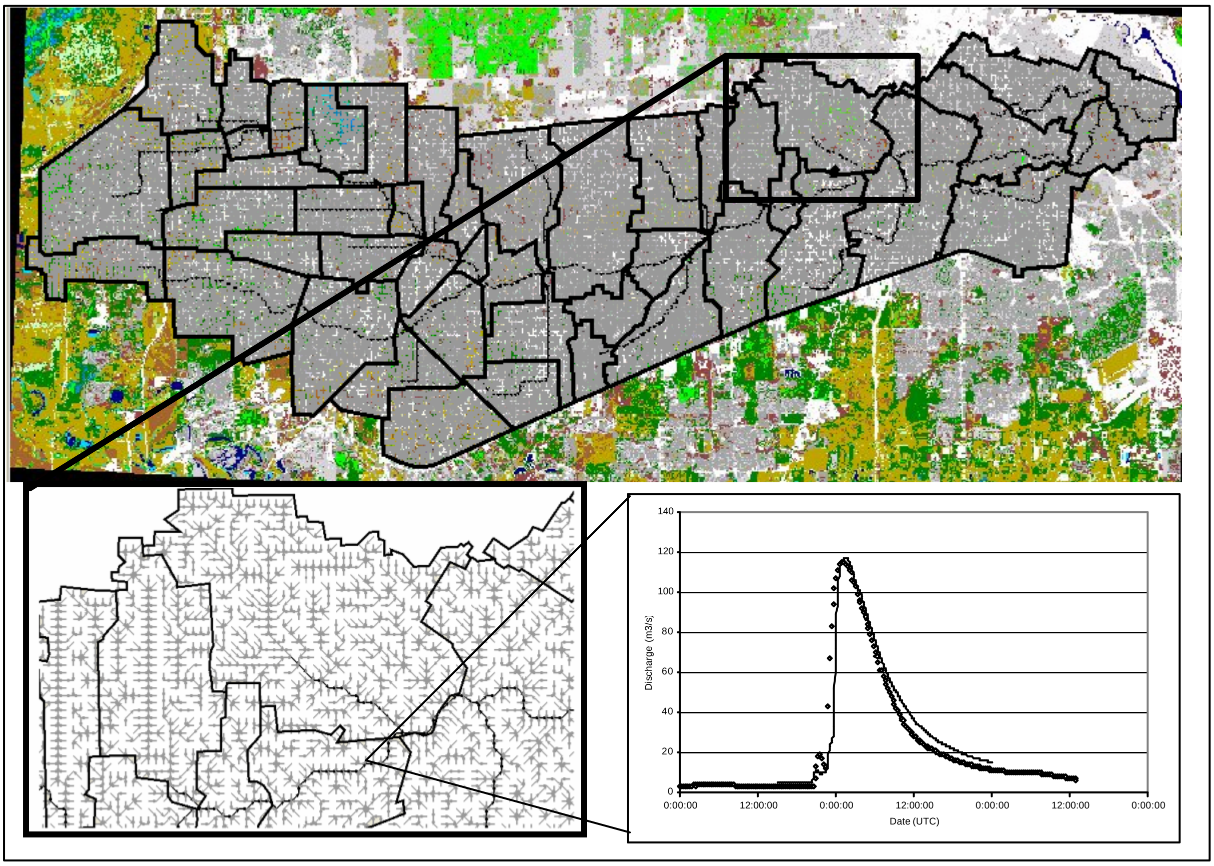

Figure 5. Vflo drainage network map of overland flow hydraulic roughness (upper and lower left image). A hydrograph produced at Main Street is shown in the lower right.

SUMMARY

Stormwater runoff significantly impacts flooding and water quality in urban areas. Operation of radar-based distributed flood forecasting systems relies on radar and gauge rainfall rates as input. The complex interaction of QPE input with drainage infrastructure presents challenges to the design of stormwater drainage infrastructure, the management of flooding, flood mitigation, and real-time forecasting of multi-scale urban drainage systems with multi-sensor inputs. Advances in stormwater runoff modeling and radar technology for the detection and forecasting of complex precipitation patterns, help characterize the performance of urban drainage infrastructure at both regional and local scales. Improvements in technology such as real-time radar rainfall, automatic stream gage systems, and automated data reporting dissemination via the Internet have made it possible to develop and operate customized site-specific warning systems. Real-time runoff prediction using radar and rain gauge input is supported by a distributed, physics-based hydrologic model capable of utilizing geographic information and multi-sensor precipitation input to simulate rainfall runoff from rural and urban catchments.

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