J1.3 EVALUATION OF URBAN HYDROLOGIC PREDICTION ACCURACY FOR REAL-TIME FORECASTING USING RADAR

Baxter E. Vieux*, University of Oklahoma, Norman, OK 73019, and
Philip B. Bedient, Rice University, Houston, TX

1. ABSTRACT

Radar measurement characteristics have important consequences on the predictability of flood hazards in urban watersheds. Site-specific hydrologic prediction is made possible by high-resolution geospatial data and physics-based distributed modeling. Within the urban context, basin response is typically less than one-hour and basin sizes less than several hundred square kilometers. Forecast locations within such basins could be as small as 10 km^2 and grid cell resolutions on the order of 100 meters. Two main issues affecting predictability at these time and space scales are accuracy of quantitative precipitation inputs and the hydraulic characteristics used by the model simulate runoff processes. Operational system simulation experiments (OSSEs) help identify performance characteristics of the distributed flood forecasting system. Through event reconstruction, existing system performance is assessed using input from the NWS WSR-88D (NEXRAD) to create model forecasts for past events. A new network of radars is being developed as part of an Engineering Research Center testbed, called TEXRAD. Considerable insight into system improvements, adaptations, and applicable watershed scales is expected from the OSSE. Once the new radar network is in place, comparisons of flood forecast accuracy can be made between existing and developmental systems.

2. INTRODUCTION

One of the most important sources of hydrologic forecast uncertainty derives from rainfall inputs. Spatial patterns of rainfall input are not always resolved adequately by rain gauges. Remote sensing of the spatial pattern and quantity of rainfall has been advanced by the use of weather radar. The ability of radar to accurately measure precipitation depends on the characteristics of the radar system for detecting hydrometeor, e.g., rain, snow, hail and other forms.

* *Corresponding author address:* Baxter E. Vieux, Univ. of Oklahoma, School of Civil Engineering and Environmental Science. Norman, OK 73072;
e-mail: bvieux@ou.edu

Radar characteristics and system design affect the usefulness of radar-derived or multisensor QPE for hydrologic applications. Spatial variability of radar-measured rainfall and its accuracy, is a leading determinant in hydrologic prediction uncertainty Assessing the propagation of uncertainty associated with rainfall inputs and parameters shows that spatial resolution has important effects on the hydrologic prediction accuracy (Vieux, 1993; Vieux, 2001; Vieux and Moreda, 2003).

Ability of radar to provide accurate rainfall estimates over large areas at high resolution depends on the characteristics of the radar and surrounding terrain. The WSR-88D radar is a 10-cm wavelength (S-band) radar deployed in the US by the National Weather Service (NWS). Its design is for long-distance surveillance given the ability of 10-cm wavelengths to penetrate the atmosphere and rainfall with little attenuation. With a 10-cm wavelength, under most conditions, the useful range is considered 180 km even though the WSR-88D 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 roughly 3.5 km AGL and may overshoot low clouds.

Long-range surveillance of severe weather is critical to the mission of the NWS for providing general flood warning to the public, e.g., by county areas. However, site-specific urban flood forecasting benefits from having radar coverage specifically designed for small basins that have short response times. WRS-88D radar installations are known to have blockages (buildings, radio towers, etc.) that can result in areas not being covered or served by the radar. While such blockages may be a minor fault for NWS-type weather surveillance over large regions, they can pose fundamental limitations in urban areas. A further limitation that can influence radar rainfall accuracy is precipitation overshoot. At long distances, precipitation can go undetected due to the AGL height of the WSR-88D beam. Especially in urban basins, post-processing is necessary before radar can be used for hydrologic applications. Comparisons of existing system forecast accuracy is a useful first step in the development of a new radar system designed specifically for flood forecasting in urban basins.

2. WATERSHED TESTBED

Brays Bayou is located in Houston Texas. It is an urban basin that responds to rainfall within 1 or 2 hours. Due to Houston's coastal proximity, tropical storms and abundant gulf moisture makes intense and prolonged rainfall a common occurrence that results in major flooding every 5 to 10 years. The land surface slopes in Brays Bayou are quite flat. Some areas have model slopes as low as 0.001%. Three USGS gauging stations are located in Brays Bayou at Main Street (241 km^2), Gessner (136 km^2), and Roark Road (31 km^2). An additional area of interest called Harris Gully is 10km^2 and has the potential to cause localized flooding. The flood potential in Brays and much or Houston is high due to urbanization, clay soils, and an urban drainage infrastructure that accelerates local runoff to downstream areas. Chronic flooding in Brays Bayou has brought attention to development of systems for forecasting floods at specific locations.

The Texas Medical Center (TMC), Rice University, and others have developed a custom flood warning system to create a site-specific forecast system. The Rice University/TMC Flood Alert System (www.floodalert.org) provides critical flood information to the member institutions of the TMC. Information derived from this system supports operations and logistical measures designed to reduce flood losses. 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. When flooding is imminent in Brays Bayou (adjacent to the medical center), specific actions are taken that include placing member institutions on alert, closing floodgates, or suspending patient care and evacuating the hospitals/facilities. The forecast point of interest for 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. Further details on this system may be found in FAS (1998); Bedient et al. (2000); Bedient et al. (2002); HCFCD (2000); and Bedient et al. (2003).

Short-term hydrologic prediction accuracy for this urban basin is being evaluated using an existing real-time continuous radar-based flood alert system that serves the TMC and other organizations (public and private) in the Houston metropolitan area. The NetRad radar network is part of the NSF-funded Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA). This recently funded center is a collaborative effort by University of Massachusetts Amherst, University of Oklahoma, Colorado State University, and University of Puerto Rico, Mayagüez (www.casa.umass.edu).

NetRad is being deployed as a system-level testbed during the first five years of this ERC. It is composed of dense networks of small, geographically fixed low power multiple-beam radars that resolve precipitation and other atmospheric structures from the ground to the middle troposphere with spatial resolution on the order of 100's of meters. The first NetRad system will be installed in the Oklahoma testbed for detection of severe weather, specifically, tornados. Once this system has been developed, a refinement will result in a radar system more adapted to quantitative precipitation measurement called TEXRAD. This new network will be installed in the Houston testbed.

The Houston testbed is planned for the development of radar technology that produces sufficiently accurate rainfall to make real-time flood predictions that are useful for specific logistical actions, e.g., shutting flood gates, alerting emergency personnel, and closing building entrances where flood waters may enter. Flood forecasts require not only detection of precipitation but also a model of the urban drainage infrastructure. A distributed hydrologic model that uses remotely sensed rainfall is coupled within an integrative framework to provide operational flood forecasts. Radar remote sensing adapted specifically for measuring the inputs is needed for real-time flood forecasting at high resolution over urban areas. The TEXRAD system is being designed for this purpose. Figure 1 shows a schematic for TEXRAD. Initially, radars will be installed covering Brays Bayou with an initial radar placed at the TMC.

The unique feature of the CASA radar system is that it will be composed of a network designed from the outset for urban flood forecasting using distributed hydrologic modeling. Rather than adapting an existing WSR-88D for hydrologic purposes, the new system will be designed specifically for hydrologic model input. Testing of quantitative precipitation estimates derived from the experimental radar network and from the WSR-88D radar will be possible. The proximity to an existing WSR-88D radar (KHGX) will provide the opportunity to compare flood forecasting accuracy with input from the two radar systems, TEXRAD and NEXRAD.

The goal of the TEXRAD system and testbed is to go beyond simply comparing radar QPE to rain gauges for statistical validation, but to validate the QPE hydrologically within a flood forecast system. This will be achieved by performing the OSSE with various radar and simulated inputs. Once the TEXRAD system is in place then direct comparisons can be made with the WSR-88D. More importantly, the improvement in prediction accuracy for small subbasins (e.g., 10 km^2) within Brays will be identified.

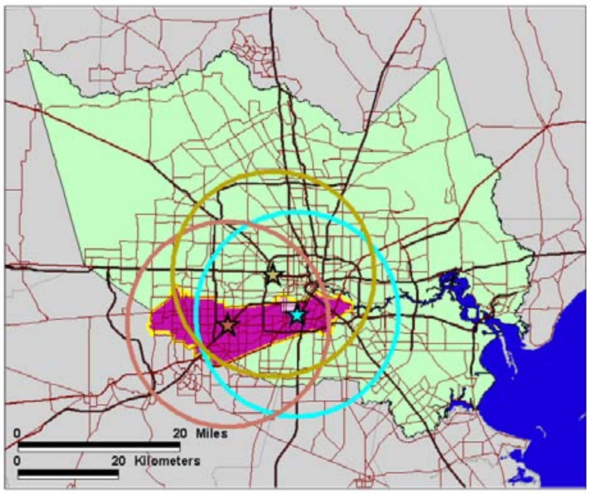

Figure 1 Schematic for the TEXRAD urban hydrologic engineering testbed for testing quantitative precipitation estimates from radar networks. Harris County and surrounding counties are shown. The star symbols indictate initial placement of radars including a radar located at the Texas Medical Center.

3. RADAR DESIGN CHARACTERISTICS

The target scale of TEXRAD is to provide quantitative precipitation measurements for urban basins that range in size from 10 to 100's of km^2. Radar design characteristics that are important to quantitative precipitation measurement include data precision, spatial and temporal resolution, sensitivity, and accuracy. Data precision is important because reflectivity reported in increments of 5 dBZ, e.g., Level III WSR-88D image products, are too coarse to be useful for quantitative applications (Crum and Alberty, 1993). Table 1 shows how rain rates increase in steps of 5-dBZ steps when using the Tropical Z-R relationship ($Z=250R^{1.2}$). The difference between 45 and 50 dBZ is the difference between 56 and 147 mm/hr. If low-precision (5-dBZ) radar measurements are used, then achieving accurate rainfall measurement will not be possible. Attenuation during heavy rain is especially important in this application because of the intense rainfall produced by frequent tropical storms. Tropical Storm Allison was measured by radar and rain gauges with intensities of approaching or exceeding 100 mm/hr (4 in/hr). For description of this event and details about the existing urban flood alert system, see Bedient et al. (2003). Lesser intensities, if prolonged, can cause flooding in the flat coastal terrain making the lower range of reflectivity important as well. Resolving locally intense rainfall and associated gradients requires high temporal resolution. The necessary temporal updates will also depend on the size of the urban drainage basin and its response time. Accuracy of the quantitative precipitation measurement is expected to be improved through dual polarization. Spatial resolution of the radar sample volumes will be on the order of several 100 meters or less. Sample volume resolution is expected to be consistent with the resolution of an existing distributed model flood forecasting system in place for the Texas Medical Center.

Table 1 Data precision influence on rainfall rate

Reflectivity (dBZ)	**Rainfall (mm/hr)**	**Rainfall (in/hr)**
25	1.22	0.048
30	3.17	0.125
35	8.29	0.326
40	21.63	0.852
45	56.46	2.223
50	147.36	5.802
55	384.64	15.143

4. DISTRIBUTED HYDROLOGIC MODELING

The distributed hydrologic model called V*flo*™ is used operationally to forecast flooding for the TMC with input from the WSR-88D radar, KHGX located approximately 50-km away from Brays Bayou. V*flo*™ uses the finite element solution to the kinematic wave equations (Vieux and Vieux, 2002; Hunter et al. 2003a,b; Vieux et al., 2003; and Vieux and Bedient, 2003). Conservation of mass together with an appropriate relation between velocity, u, and flow depth, h, such as the Manning equation, results in:

$$\frac{\partial h}{\partial t} + \frac{s^{1/2}}{\beta n}\frac{\partial h^{5/3}}{\partial x} = \gamma R - \alpha I \qquad (1)$$

where, the three scalars α, γ, and β are the multipliers controlling, infiltration rate, I; rainfall rate, *R*; hydraulic roughness, *n*; and *s* is the principal land-surface slope at the center of each grid cell. These scalars multiply the values contained in the spatially variable parameter maps. The Ordered Physics-based Parameter Adjustment (OPPA) methodology described by Vieux and Moreda (2002) is used to adjust these scalars over a physically-realistic range with the intent of preserving the spatial variability of the underlying parameter map. Differential application of the roughness scalars to channel and overland are designated β_c and β_o. The slope and hydraulic roughness variables in Eq. 1 are spatially variable, while rainfall, infiltration, and flow depth are both spatially and temporally variable. A value of γ=1.0 represents no bias (systematic error). This rainfall factor may be adjusted within the model if not accounted for independently through gauge-adjustment of the radar QPE. Figure 2 shows the model overview for Brays Bayou.

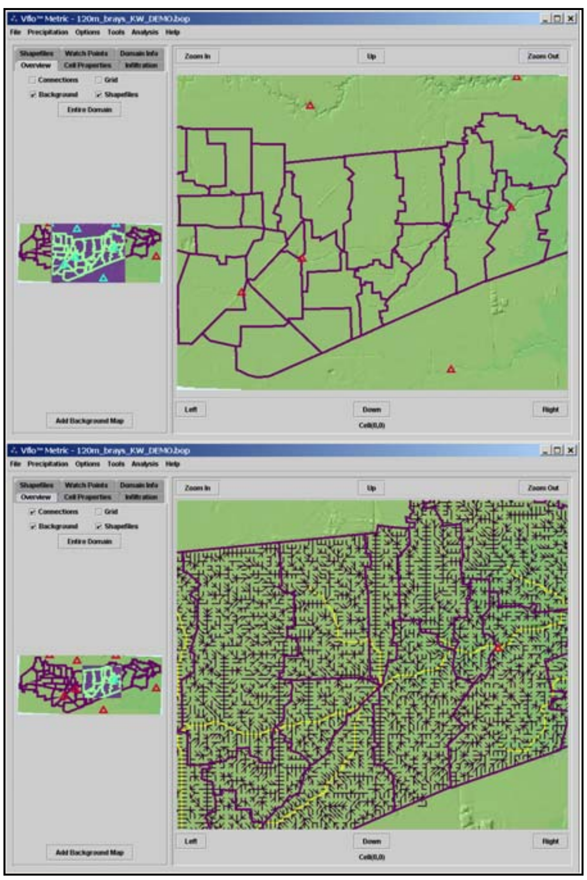

Figure 2 Computational model (V*flo*™) for Brays Bayou zoomed over Main Street. Top panel shows a shaded relief map of Brays between Main Street and Gessner. Bottom panel shows the finite element connections between each 120 meter model resolution.

Geospatial data is used to represent soils/infiltration, land surface slope and drainage connectivity, and landuse/cover for hydraulic roughness parameters. Finite elements connect each grid cell together, which is then used to solve the kinematic wave equation (Eq. 1). The digital elevation model (DEM) is based on a LiDAR bare earth model sampled to 30 meter resolution (top panel). The model computational resolution is 120-m, which are connected by finite elements (bottom panel).

4. EVALUATION OF FORECAST ACCURACY

Reconstructing events from archive radar rainfall, stream and rain gauges provides important information regarding expected forecast accuracy during actual events and helps guide development of the TEXRAD system. Details on the forecast accuracy of the existing system using the WSR-88D radar may be found in Vieux and Bedient (2003). The operational model was developed by adjusting overland and channel hydraulic roughness parameter maps to minimize rising limb differences for several storm events. The calibrated model is continuing to be validated operationally. Table 2 shows normalized peak values (divided by 1000 m^3/s). Observed discharge (**Qo**) and simulated (**Qs**) are peak discharge values at the two gauging stations. While, there is only one validation event reported here (15 August 2002), it shows excellent agreement at Main Street and at an interior location. Figure 3 shows the normalized peak discharge at Main Street and Gessner.

Table 2 Normalized peak values for the four events and a fifth validation event.

Event	Main Street		Gessner	
	Qo	**Qs**	**Qo**	**Qs**
Francis	0.73	0.75	0.32	0.52
Allison 1st	0.49	0.38	0.09	0.07
Allison 2nd	0.41	0.46	0.21	0.29
Allison 3rd	0.86	0.91	0.32	0.28
8/15/2002	0.51	0.60	0.22	0.22

Table 3 shows comparative forecast accuracy for the two locations. On average, a bias of 1.2143 indicates a 21% over-prediction at Gessner, whereas at Main, the bias is nearly 1.0. The validation event showed no bias at Gessner (Qo=0.22 compared to Qs=0.22) and a 9% over prediction (Qo=0.51 compared to Qs=0.60) at Main Street.

More detailed quantitative precipitation inputs from TEXRAD and improvements made to the hydraulic characteristics included in the model are expected to increase prediction accuracy for small urban areas. Once TEXRAD comes online, model forecasts using input from both radar systems, TEXRAD and NEXRAD, will afford considerable insight into system improvements, adaptations, and applicable watershed scales.

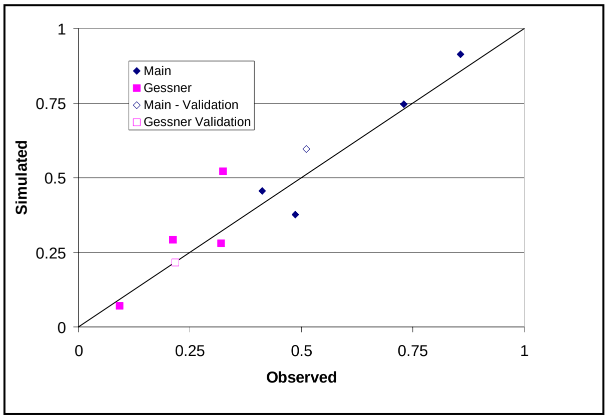

Figure 3 Normalized discharge for five events. Calibration events are shown with filled diamonds and squares for Main and Gessner. The validation event at Main Street and Gessner is shown with an unfilled diamond and square, respectively.

Table 3 Comparative model efficiency at Main and Gessner for the five events.

Statistic	Main	Gessner
Bias	1.0361	1.2143
R^2	0.8824	0.6863

5. SUMMARY

Radar systems provide high-resolution precipitation measurements that are useful for urban hydrologic applications. The CASA ERC is developing advanced quantitative precipitation estimates using a network of low cost radars. Radar measurement characteristics have important consequences on the predictability of urban watersheds. Operational system simulation experiments provide guidance on design of quantitative precipitation estimates for distributed hydrologic modeling. Event reconstruction with WSR-88D radar shows that distributed hydrologic model is capable of producing accurate and site-specific forecast. Future comparative studies will be conducted to reveal needed system improvements and adaptation for use in flood forecasting in watersheds that produce flood hazards in urban areas. The results of such experiments help assess prediction accuracy and predictability limits in support of continuous real-time flood alert system operation. The goal of this system is to provide low-cost radar rainfall designed for urban flood forecasting using a distributed physics-based hydrologic model.

6. ACKNOWLEDGEMENT

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7. REFERENCES

Bedient, P.B., A. Holder, J.A. Benavides, and B.E. Vieux, 2003: Radar-Based Flood Warning System–Tropical Storm Allison. J. of Hydrologic Engineering, November/December, 8(6), pp. 308-318.

Bedient, P. B., B. C. Hoblit, D. C. Gladwell, and B. E. Vieux, 2000. “NEXRAD Radar for Flood Prediction in Houston,” J. of Hydrologic Engineering, 5(3): 269-277.

FAS, 1998. TMC/Rice University Flood Alert System. Available on the Internet at: www.floodalert.org. Last accessed, 10 November 2003.

HCFCD, 2000. Project Brays, Harris County Flood Control District, Houston, Texas.

Hunter, S., B.E. Vieux, F. Ogden, J. Niedzialek, C. Downer, J. Addiego, and J. Daraio, 2003a. A test of two distributed hydrologic models with WSR-88D radar precipitation data input in Arizona. 31st International Conference on Radar Meteorology American Meteorology Society, P9.5, Abstract and paper.

Hunter, S., B.E. Vieux, F. Ogden, J. Niedzialek, C. Downer, J. Addiego, and J. Daraio, 2003b. A test of two distributed hydrologic models with WSR-88D radar precipitation data input in Arizona. 17th Conference on Hydrology, American Meteorology Society, JP3.3, Abstract and paper.

Vieux, B. E. and P. B. Bedient, 1998. “Estimation of Rainfall for Flood Prediction from WSR-88D Reflectivity: A Case Study, 18–18 October, 1994,” Journal of Weather and Forecasting, 13(2): 407-415.

Vieux, B.E. and J.E. Vieux, 2002. V*flo*™: A Real-time Distributed Hydrologic Model. Proceedings of the 2nd Federal Interagency Hydrologic Modeling Conference, July 28-August 1, 2002, Las Vegas, Nevada. Abstract and paper on CD-ROM.

Vieux, B.E., and F.G. Moreda, 2003. Ordered Physics-Based Parameter Adjustment of a Distributed Model. In, Advances in Calibration of Watershed Models, Edited by Q. Duan, S. Sorooshian, H.V. Gupta, A.N. Rousseau, R. Turcotte, Water Science and Application Series, 6, American Geophysical Union, ISBN 0-87590-355-X: 267-281

Vieux, B.E. and P.B. Bedient, 2003: Assessing urban hydrologic prediction accuracy through event reconstruction. J. of Hydrology, Special Issue in Urban Hydrology. Forthcoming.

Vieux, B.E., C. Chen, J.E. Vieux, and K.W. Howard, 2003: Operational deployment of a physics-based distributed rainfall-runoff model for flood forecasting in Taiwan. In proceedings, International Symposium on Weather Radar Information and Distributed Hydrological Modelling, IAHS General Assembly at Sapporo, Japan, July 3-11, 2003. eds. Tachikawa, B. Vieux, K.P. Georgakakos, and E. Nakakita, IAHS Red Book Publication No. 282: 251-257.