# NEXRAD Radar for Flood Prediction in Houston

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**Abstract:** Due to a number of hydrologic and meteorologic factors, Houston, Texas, is subject to major flooding problems. The National Weather Service's (NWS) WSR-88D radar (NEXRAD) was used to estimate the areal and spatial distribution of rainfall for three storms over the Brays Bayou watershed in Houston for hydrologic modeling purposes. Rainfall rates estimated from the NEXRAD radar compared favorably to the point rainfall measurements at the operating rain gauges in the watershed for the large October 1994 storm, but tended to overpredict the point rainfall measurements at the rain gauges for two smaller events. Using HEC-1, two model runs were made using the unadjusted NEXRAD-estimated rainfall rates and also using the rain gauge network, and the modeled outflow hydrographs were compared to the measured hydrograph for all three storms. The results from the radar proved to be as accurate, and in some cases more accurate, than the rain gauge model when predicting runoff volume, peak flow, and time of peak. Results from this research are being used to create a local flood warning system on the Brays Bayou watershed using real-time NEXRAD radar.



## INTRODUCTION

Flooding is considered the number one natural disaster in the United States. According to the National Weather Service (NWS) data for the period between 1940 and 1982, flooding caused an average of 102 fatalities and about $1.5 billion in property damage per year (NWS 1985). 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. Many flash flood warnings are issued with less than a one hour lead-time, and half of the issued warnings provided no lead-time whatsoever (NWS 1982).

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 (Schell et al. 1992) and can produce very intense rainfall rates that lead to localized flooding (Doswell et al. 1997). Houston, Texas, has suffered from massive flooding problems for many years due to the intense nature of Gulf Coast rainfalls, rapid urban development with concrete channels, generally clay soils with low infiltration capacity, high runoff rates, and mild slopes.

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 needed for flood prediction and warning. 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 examine the contrasting detection capabilities of the NEXRAD and rain gauge networks.

The primary focus of the research was to determine if a real-time flood prediction system based on WSR-88D precipitation products could yield accurate and timely flood forecasts for an urban watershed. The analysis focused on Brays Bayou, a fully developed watershed in Houston, and three rainfall events: October 1994, April 1997, and January 1998. The October 1994 event was a major storm and flood that produced more than 60 cm of rainfall over parts of the Texas Gulf Coast near Houston in a three day period and caused extensive flooding damage throughout southeast Texas (Liscum and East 1995).

### Flood Prediction Systems

During the late 1970s, the first of the Automated Local Evaluation in Real Time (ALERT) systems was deployed 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. The system in Houston was installed in 1983 and has evolved into over 80 rainfall and steamflow gauges for the 20 watersheds that generally drain the city. The Harris County Office of Emergency Management (HCOEM), which has responsibility for interacting with the NWS, the media, and other emergency organizations, operates the ALERT system in Harris County (HCOEM 1999).

### NEXRAD Radar Development

The WSR-88D system is the new Doppler weather radar originally deployed in a joint effort by the Departments of Commerce, Defense, and Transportation since 1992 (Crum and Alberty 1993). NEXRAD is a 10 cm wavelength radar that records reflectivity, radial velocity, and spectrum width of reflected signals. The radar is a volume scanning radar, meaning that it employs successive tilt angles to cover an entire volume of the atmosphere and can measure reflectivity up to a range of 460 km. Depending on the current weather conditions, a specific volume coverage pattern (VCP) is used that varies the number of revolutions per tilt angle and therefore varies the length of each complete volume scan. A more complete description of these and other meteorological data products and processing may be found in Crum and Alberty (1993), Doviak and Zrnic (1993), Klazura and Imy (1993), Smith et al. (1996), and Fulton et al. (1998).

The radar reflectivity is collected at 1 km in range or distance from the radar station and at one degree radial resolution,

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J. Hydrol. Eng. 2000.5:269-277.

producing a radial coordinate system of reflectivities for each tilt angle (Crum and Alberty 1993). Data at this stage are called archive level II data and consist of raw reflectivity, radial velocity, and spectrum width. The Precipitation Processing System (PPS) produces four rainfall estimation products, referred to as archive level III data: one hour accumulation, three hour accumulation, storm total accumulation, and the hourly digital precipitation array. Archive level III data are presented in rectangular coordinates with an approximate resolution of 16 $km^2$ and are available real-time to the public via NEXRAD Information Dissemination Service (NIDS) vendors (Fulton et al. 1998) and archived at the National Climatic Data Center.

Until the advent of the NEXRAD system, gauging stations had been the only source of rainfall data for hydrologic modeling and flood prediction. Gauge data are usually areally weighted using Thiessen polygons or the isohyetal method, which assigns a rainfall distribution to a specific area associated with a point measurement (Bedient and Huber 1992). Archive level II data can be translated from their original radial coordinates into a gridded coordinate system with 1.0 $km^2$ resolution. Fulton el al. (1998) and Smith et al. (1996) both provide a description of radar applications and errors associated with precipitation estimates derived from reflectivity.

Vieux and Farajalla (1996), Mimikou and Baltas (1996), and James et al. (1993) discussed the accuracy of radar compared to point rainfall values from gauges. A study by Johnson and Dallman (1987) indicates that one high-resolution radar station can monitor a total area of 200,000 $km^2$ with less than a 5 $km^2$ resolution. Collier (1986) found that a very dense network of gauges is needed to achieve the kind of accuracy that a radar can produce. Rainfall gauge systems limit the obtainable spatial accuracy that NEXRAD provides, but are highly effective for calibration purposes. When calibrated radar data were input into a hydrologic model, the hydrograph's rising limb and peak flow proved to be more accurate than the hydrographs produced from the rain gauge data alone (Mimikou and Baltas 1996).

## Rainfall Estimation

To use the archive level II raw reflectivity in hydrologic modeling, it must be converted to rainfall rates. Basic meteorological relationships between reflectivity and rainfall rate allow for an accurate estimation of rainfall, both spatially and temporally. Rainfall rates can be obtained from the NEXRAD radar using the basic relationship between rainfall rate, $R$ (mm/h), and reflectivity $Z$ (dBZ). The ''standard'' $Z$–$R$ relationship used at the time of the WSR-88D deployment is $Z = 300R^{1.4}$, but the Houston-Galveston NWS Forecast Office (KHGX) has since adopted the ''tropical'' $Z$–$R$ relationship ($Z = 250R^{1.2}$), which is more representative of warm tropical rainfall drop distributions due to underestimation of rainfall totals. Anomalous clutter produces low level dBZ and is suppressed using a floor of 25 dBZ. Hail is usually considered to be present above 51–55 dBZ, and for this reason a high reflectivity cutoff is used to eliminate its effect on precipitation rate estimates (Fulton et al. 1998). The two different $Z$–$R$ relationships are compared in Table 1 for a typical range of reflectivities (dBZ).

Rainfall rates for each subbasin within a watershed area can be determined using the appropriate $Z$–$R$ relationship. The accumulated rainfall depths can be determined by the integration of the rainfall intensity for the duration between each volume scan, which is 6 min for VCP 21 (Vieux and Farajalla 1996). The use of the correct $Z$–$R$ relationship is critical for the development of accurate rainfall estimates. For example, during the massive October 1994 rainfall event in southeast Texas, Lott and Sittel (1996) reported that the NEXRAD radar at KHGX underestimated the rainfall by as much as 50% using the standard $Z$–$R$ relationship. Baeck and Smith (1998) showed a similar underestimation by the radar using the standard relationship at Spring Creek, located in north Houston, and an even greater underestimation at Lake Livingston, located about 100 km north of downtown Houston. One possible reason was the use of the standard $Z$–$R$ relationship during the storm, which did not accurately characterize the warm subtropical air mass that produced the heavy rains. Vieux and Bedient (1998) showed that the tropical $Z$–$R$ relationship was more accurate for October 1994 for the Gulf Coast region, as described later in this paper.

**TABLE 1. Comparison of $Z$–$R$ Relationships**

| Reflectivity (dBZ) (1) | Rainfall Rate (cm/h) Standard (2) | Rainfall Rate (cm/h) Tropical (3) |
|---|---|---|
| 25 | 0.10 | 0.12 |
| 30 | 0.24 | 0.32 |
| 35 | 0.54 | 0.83 |
| 40 | 1.22 | 2.16 |
| 45 | 2.79 | 5.65 |
| 50 | 6.34 | 14.74 |
| 53 | 10.38 | 26.20 |

## Hydrologic Models

Hydrologic models of a watershed can be used with rainfall input and physiographic features to predict flood hydrographs for analysis and evaluation. Once calibrated, the model can be used to predict a watershed's response to any rainfall event. There are a number of possible choices for lumped parameter or distributed hydrologic models that could be used. The distributed models consider surficial characteristics such as soils, land cover, and topography directly and use numerical methods to develop hydrograph response (Vieux and Gaur 1994). Though several of these distributed models exist, the general practice still relies heavily on the use of lumped parameter hydrologic models.

The HEC-1 flood hydrograph package is one of the most widely used lumped parameter models for hydrologic prediction and has seen extensive use in Texas for the determination of local hydrographs and peak flows. HEC-1 simulates the runoff response of a river basin to rainfall by representing a watershed as an interconnected system of hydrologic and hydraulic components. Each component requires a set of parameters that specify the mathematical relations that describe the rainfall-runoff processes (HEC 1990). HEC-HMS, a windows-based graphically oriented update of HEC-1, was released in March 1998 and is designed to eventually replace HEC-1 (HEC 1998). However, HEC-1, as well as other hydrologic models, suffers from the lack of spatial and temporal rainfall input when only a few rain gauges are available in a watershed. One objective of this study is to demonstrate that HEC-1 results can be improved over gauge estimates by using NEXRAD rainfall distributions. Several storms were analyzed using gauged data and NEXRAD, and then hydrographs were compared at the outlet of the watershed.

## APPLICATION TO BRAYS BAYOU WATERSHED

Flooding conditions in the Texas Gulf Coast and in the Houston area have increased significantly over the past 30 years as increases in urbanization have caused local watersheds to respond more quickly and with higher peaks to moderate to heavy rainfall. Liscum and Massey (1980) show between a four- and five-fold increase in the peak discharge in Houston watersheds when a watershed is converted from completely rural to completely urban and when the channel is transformed from completely rural to completely rectified and



J. Hydrol. Eng. 2000.5:269-277.

concrete-lined. Harris County and a number of other communities in southeast Texas have been advised to initiate a voluntary property buyout program, due to a history of severe flooding (NWF 1998). Because of a number of factors, including intense rainfalls and clay soils (SCS 1976), Houston is very susceptible to localized flooding. In one devastating year, 1979, flooding in the Houston area accounted for approximately 50% of the flood damages in the United States (Rice Center 1980). Major floods also occurred in 1989, 1992,1994, and 1998 over various parts of the city and county.

The Brays Bayou watershed covers 334 km$^2$ and has been divided into 43 subbasins for hydrologic analysis (Fig. 1). The bayou extends from far western Houston suburbs east to its confluence with the Houston Ship Channel, a total length of approximately 50 km. The upper watershed (upstream of the USGS stream Gauge 08075000 and HCOEM rain Gauge 420 at Main Street) drains an area of approximately 246 km$^2$ and includes the Texas Medical Center, Rice University, and the museum district, along with other major urban centers. The HCOEM currently has six operating gauges as part of the county ALERT system in the upper watershed that records water levels and rainfall during storm events (Fig. 1). Note that Gauge 400 is downstream of the outlet of the study area, but is in close enough proximity to be included in the analysis.

Originally a natural channel that was subject to frequent flooding, Brays Bayou was deepened, widened, and partially concrete-lined in the early sixties by the U.S. Army Corps of Engineers as part of a flood control project. The original channelized bayou was designed to contain greater that a 100 year storm event with bankfull capacity of 820 m$^3$/s (29,000 ft$^3$/s) at the Main Street gauge (Gauge 420 in Fig. 1). The response time of the watershed was shortened significantly and the peak flows were increased due to increased lateral drainage and urban developments.

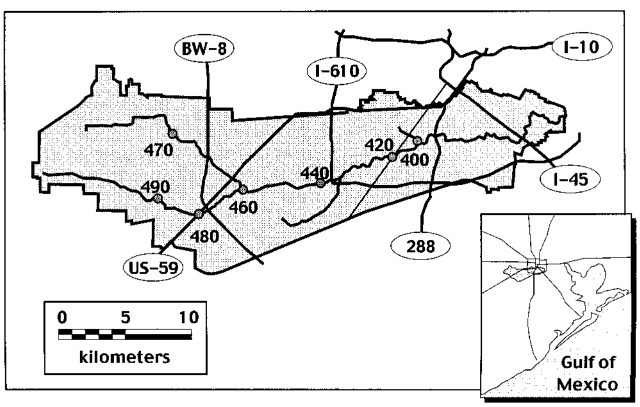


FIG. 1. Brays Bayou Watershed with HCOEM Rain Gauges

Between the late sixties and early nineties, Houston went from a moderately sized city to the fourth largest city in the United States. Within 15 years of the completion of the main channel, the design capacity of the bayou had decreased to about a 5 to 10 year design storm (14.5 cm of rainfall in six hours) due to increased urbanization and the addition of extensive lateral drainage to support development. In 1976 and again in 1983, major rainfalls caused significant flooding to occur along the banks of the bayou (Juch 1985), and watershed plans were developed to divert part of the watershed to other areas in 1985. However, these plans were not implemented due to political issues and the significant downturn in the economy of Texas in the eighties. By 1993, the Brays Bayou watershed had become over 90% developed with primarily commercial and residential properties, thus significantly lowering the design capacity of the bayou.

A flood warning study conducted on Brays Bayou watershed by Fisher (1993) found that each historical storm produced hydrographs at Main Street with very similar slopes of the rising limb (Fig. 2, adapted from Fisher 1993). Brays Bayou has an extremely fast response time, resulting in a lag time of about 4.0 h, measured from the center of mass of rainfall. White Oak Bayou, located approximately 10 km north of Brays Bayou and also concrete-lined and heavily urbanized, has a similarly short lag time. The fast response time, therefore, does not give much advanced warning for a flood warning system. It was also found that upstream bayou conditions at Gessner Drive (Gauge 460 in Fig. 1) cannot help with the flood prediction process due to the simultaneous peak times observed at Gessner Road and Main Street for past bayou storms, such as the January 1998 event shown in Fig. 3. Based on the analysis of the bayou's response to a storm event, Fisher developed a flood prediction system related to the inflection point of a hydrograph's rising limb during a real-time storm event. From the 1993 study of hydrograph response, the flood

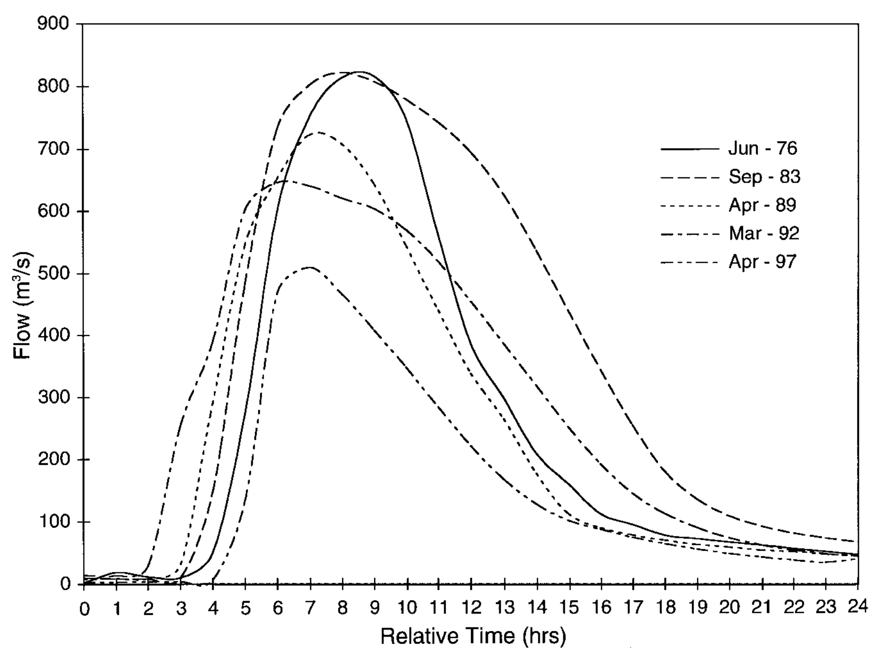


FIG. 2. Five Historical Storm Hydrographs on Brays Bayou (USGS Gauge 08075000) Showing Similar Rising Limb Slopes



J. Hydrol. Eng. 2000.5:269-277.

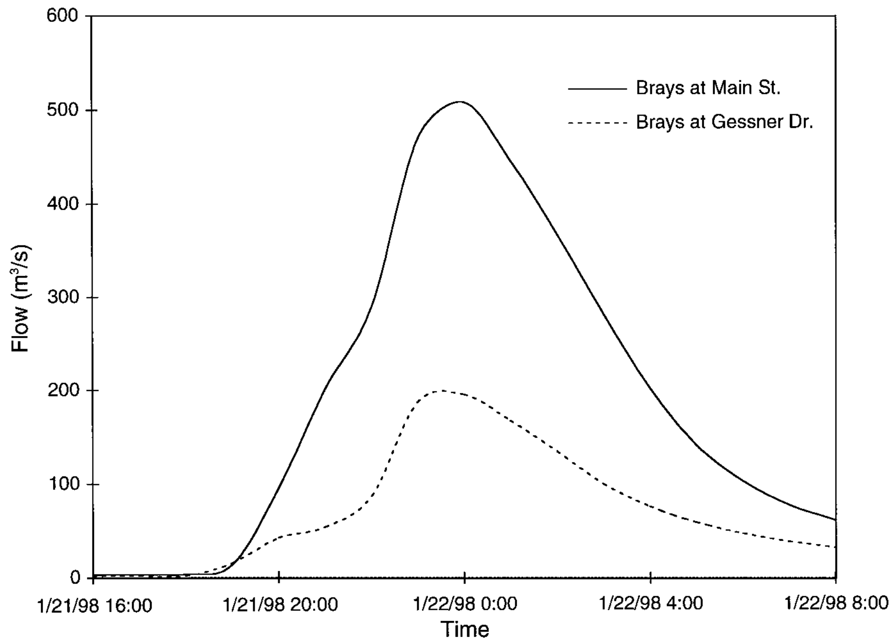


**FIG. 3. Simultaneous Peaks on Brays Bayou at Main Street and Upstream at Gessner Drive for January 1998 Storm**

warning system on the bayou could provide only about one hour of lead time prior to bankfull conditions.

Given the above difficulties, and with the availability of WSR-88D radar systems in Houston after 1992, a new effort to calibrate radar-estimated rainfall to gauge-estimated rainfall measurements and to observed hydrographs was implemented, and the results are presented in this paper. This procedure, when linked with real-time radar data, will allow a more useful and accurate flood warning system to be developed.

## METHODOLOGY

A study by Vieux and Bedient (1998) examined the applicability of using NEXRAD radar for rainfall estimation in the Clear Creek watershed near Houston for the same event. The results between measured rainfall and radar estimates were quite good, and the HEC-1 modeled hydrograph matched measured values for Clear Creek with reasonable accuracy. The methods used in the earlier study of Clear Creek were repeated for Brays Bayou, but with the addition of more direct comparison to rain gauges in the watershed and to observed hydrographs.

The first event to be analyzed with radar was the large storm that produced over 60 cm of rain in parts of southeast Texas on October 17–18, 1994 (Friday and Hassel 1995). Two other storm events in the Brays Bayou watershed were selected for in-depth analysis and comparison of gauged rainfalls to NEXRAD data. The first occurred on April 4, 1997, and resulted in about 5.0 to 7.5 cm of rainfall over five hours. The second event produced about 8.5 cm of rainfall over the Brays Bayou watershed over six hours on January 21–22, 1998.

**TABLE 2. October 17, 1994, Rainfall Data for Brays Bayou**

| Parameter (1) | HCOEM RAIN GAUGES 400 (2) | 440 (3) | 460 (4) | 470 (5) | 480 (6) | 490 (7) |
|---|---|---|---|---|---|---|
| Radar (cm) | 17.12 | 12.73 | 5.44 | 4.19 | 3.71 | 5.08 |
| Gauge (cm) | 20.07 | 11.30 | 6.10 | 6.30 | 6.86 | 6.81 |
| Bias | −0.15 | 0.13 | −0.11 | −0.33 | −0.46 | −0.25 |

Note: Mean bias = −0.20.

**TABLE 3. October 18, 1994, Rainfall Data for Brays Bayou**

| Parameter (1) | HCOEM RAIN GAUGES 400 (2) | 440 (3) | 460 (4) | 470 (5) | 480 (6) | 490 (7) |
|---|---|---|---|---|---|---|
| Radar (cm) | 6.02 | 7.16 | 9.32 | 5.49 | 11.13 | 10.54 |
| Gauge (cm) | 6.81 | 7.80 | 6.20 | 5.51 | 9.40 | 5.89 |
| Bias | −0.12 | −0.08 | 0.50 | 0.00 | 0.18 | 0.79 |

Note: Mean bias = 0.21.

**TABLE 4. April 4, 1997, Rainfall Data for Brays Bayou**

| Parameter (1) | HCOEM RAIN GAUGES 400 (2) | 440 (3) | 440 (4) | 460 (5) | 470 (6) | 480 (7) | 490 (8) |
|---|---|---|---|---|---|---|---|
| Radar (cm) | 9.96 | 8.43 | 6.30 | 8.18 | 5.79 | 7.62 | 8.53 |
| Gauge (cm) | 6.43 | 3.51 | 6.50 | 5.87 | 4.45 | 3.92 | 6.38 |
| Bias | 0.55 | 1.34 | −0.03 | 0.39 | 0.30 | 0.95 | 0.34 |

Note: Mean bias = 0.55.

### Rainfall Estimation from Radar

The NEXRAD raw reflectivity from each volume scan from archive level II data was sampled for each event from the radar-centered radial coordinate system into the Universal Transverse Mercator projection at 1.0 by 1.0 km gridded resolution (Vieux and Bedient 1998). The reflectivity was converted to rainfall using the tropical $Z$−$R$ relationship for all of the analyzed storms. A GIS-based grid system was overlaid onto the subbasin boundaries for the Brays Bayou watershed and spatially averaged over each subbasin. The data were then aggregated temporally to create rainfall durations of 30 min for each subbasin for input into the HEC-1 model. Rain gauge data were obtained from the HCOEM's homepage (www.hcoem.co.org) for use in comparing the radar-estimated rainfall to point rain gauge measurements.

The comparative analysis of the radar-estimated rainfall to the rain gauge data was accomplished by using the radar-estimated rainfall from the particular square kilometer grid that also contained the rain gauge (Vieux and Bedient 1998). The radar value was then compared to the measured gauge datum and a mean bias was determined by computing:

$$\text{Bias} = \frac{(\text{Radar} - \text{Gauge})}{\text{Gauge}}$$

A negative bias indicates that the radar underpredicted and a positive bias indicates that the radar overestimated the rainfall collected at the rain gauges. The mean bias is the arithmetic average of the biases for the particular day and watershed and provides an approximation of how well the radar is estimating the rainfall at the point locations of the rain gauge (Tables 2–4).

The NWS uses a bias estimate to determine the statistical significance of the rain gauge–radar observations that differs from the bias definition used in this paper. The bias adjustment algorithm used by the NWS calculates the ratio of the mean rainfall at the rain gauges to the mean radar-estimated rainfall at the bins containing those gauges (Fulton et al. 1998). Since the radar data were entered into the model with no adjustment to the rain gauge data, the bias estimate is used solely to determine a relative correlation of the radar and rain gauge measurements.

## Input to Hydrologic Model

The NEXRAD-estimated rainfall was entered into the HEC-1 program for the three events for the Brays Bayou watershed. HEC-1 was selected as the model since it had been extensively calibrated for the watershed from previous studies and is the accepted approach used by the Harris County Flood Control District (HCFCD) for Houston. A HEC-1 model obtained from the HCFCD for Brays Bayou was run using the rain gauge data spatially assigned using the Thiessen polygon method for each storm and the NEXRAD data. This model has been calibrated by Juch (1985), Fisher (1993), and Gladwell (1998) and is widely used in Houston today for flood control studies.

For clay soils in an urban environment, the Harris County Flood Control District (1984) suggests using an initial loss of 1.27 cm (0.05 in.) and a constant loss of 0.13 cm/h (0.05 in./h). HCFCD suggests an initial loss of 2.54 cm (1.0 in.) and a constant loss of 0.26 cm/h (0.10 in./h) for sandy soils in an urban environment. Initial lose rate of 1.91 cm (0.75 in.) and a constant loss rate of 0.19 cm/h (0.08 in./h) were used for the April 1997 and January 1998 storms. Zero loss rates were input into the October 1994 model due to antecedent rainfall that fell for two days prior to the major storm event. The outflow hydrographs were compared to the measured hydrograph, and key parameters such as time to peak, peak flow, and the total runoff volumes were analyzed to evaluate NEXRAD estimated rainfall versus gauge datum for hydrologic modeling purposes.

## RESULTS

### October 1994 Rainfall Event

The October 1994 event produced torrential rain ranging from 20 to over 60 cm of rain over 35 counties in southeast Texas on October 15–19, with the majority of rain falling over the Houston region on October 17–18. The storm caused massive flooding and destruction in numerous watersheds throughout the southeast Texas area. The U.S. Geological Survey measured a flow of about 1.6 times the 100 year flow on the San Jacinto River below Lake Houston Dam, believed to be one of the largest direct measurements of river flow ever measured in the state of Texas (Liscum and East 1995). For this event, Brays Bayou recorded its largest flow at the Main Street gauge since the flood event of September 1983.

Vieux and Bedient (1998) showed that reprocessing the NEXRAD reflectivity data using the tropical $Z$–$R$ relationship, slightly underpredicted the rainfall on October 17 and overpredicted the rainfall on October 18 for selected gauges near the Clear Creek watershed, located 15 km south of the Brays Bayou watershed. When both days are analyzed together, the mean bias was 0.03, indicating that the radar matched very well to point rainfall measurements from the rain gauges. Baeck and Smith (1998) provide a good summary of the October 1994 storm event and found a much larger bias estimate on two watersheds north of Houston, but their study used the standard $Z$–$R$ relationship.

Tables 2 and 3 show the comparison of rain gauge data collected from the HCOEM and the NEXRAD radar-estimated data for the corresponding one $km^2$ grid cell for the upper Brays Bayou watershed. Note that Gauge 420, located on Brays Bayou at Main St., did not appear to function during the storm and is left out of the tables. The tables show that, based upon the point rain gauge information, the NEXRAD underpredicted the rainfall on October 17 (mean bias = −0.20) and overpredicted the rainfall on October 18 (mean bias = 0.21) for the Upper Brays Bayou watershed. When both days are analyzed together, the mean bias is 0.01, indicating that the radar matched the point rainfall measurements from the rain gauges very well. The rainfall was quite variable over the basin, and some of the differences can be accounted for by the fact that the individual gauges are compared to approximately 1 $km^2$ of average rainfall from the radar data.

Figs. 4(a and b) demonstrate the comparison of two of the Brays rain gauges (HCOEM Gauges 400 and 440) with the radar for the October 1994 event. The cumulative mass curves clearly indicate how well the radar was able to capture the intensity and time distribution of the measured gauge data for the storm. Overall, the matches are quite acceptable, but as a second test, the radar data were entered into HEC-1 for comparison to measured hydrographs.

### April 1997 Rainfall Event

When compared to the October 1994 storm event, the April 1997 rainfall over the upper Brays Bayou watershed was relatively small. The HCOEM rain gauges measured rain in the area that ranged from 3.51 to 6.50 cm over approximately five hours. The radar measured slightly higher rainfall totals from 6.30 to almost 10 cm of rainfall. Table 4 shows the comparison of the gauge rainfall values to the NEXRAD radar-estimated rainfall totals for the storm. The mean bias of this storm was 0.55, indicating either that an overestimation of the rainfall was made by the NEXRAD radar, or that intense convective cells missed the rain gauges. The error could also have been introduced because the NEXRAD radar averages rainfall over a 1 $km^2$ grid cell, whereas the rain gauge measured rainfall at a point location.

### January 1998 Rainfall Event

Like the April 1997 event, the January 1998 storm was much smaller than the October 1994 flood event. The HCOEM rain gauges measured rain in the area that ranged from less than 1 cm to 12.29 cm over a duration of about six hours. The radar measured larger rainfall totals, ranging from about 4 to over 20 cm of rainfall over the same durations. Table 5 shows the comparison of the gauge rainfall values to the NEXRAD radar-estimated rainfall totals for the storm. Gauge 480 did not appear to function properly during the storm event. The mean bias without the gauge was 0.79, which indicates either that a major overestimation of the rainfall was made by the NEXRAD radar, or that intense convective cells missed the rain gauges.

### Modeling Storm Events on Brays Bayou

The October 1994 event over Brays Bayou was chosen to determine how well the radar-estimated rainfall predicts the



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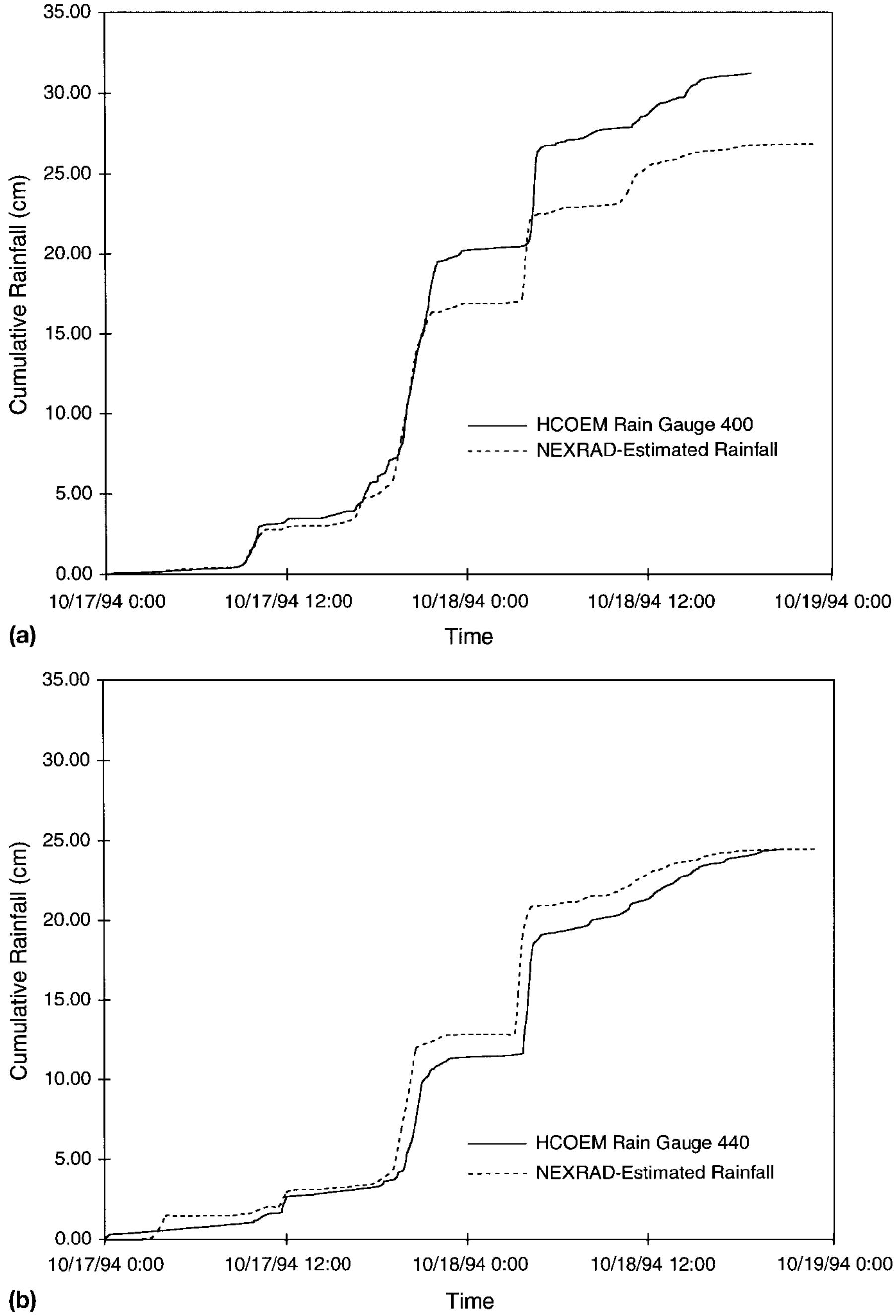


**FIG. 4. Cumulative Rainfall Comparison between Rain Gauge and NEXRAD Radar: (a) HCOEM Gauge 400 at Texas Medical Center; (b) HCOEM Gauge 440 at Rice Blvd**

**TABLE 5. January 21–22, 1998, Rainfall Data for Brays Bayou**

| Parameter (1) | HCOEM RAIN GAUGES 400 (2) | 420 (3) | 440 (4) | 460 (5) | 470 (6) | 480 (7) | 490 (8) |
|---|---|---|---|---|---|---|---|
| Radar (cm) | 20.14 | 16.82 | 13.49 | 9.98 | 6.68 | 8.00 | 4.01 |
| Gauge (cm) | 12.29 | 8.33 | 4.39 | 5.99 | 4.80 | 0.99 | 4.19 |
| Bias | 0.64 | 1.02 | 2.07 | 0.67 | 0.39 | 7.08 | −0.04 |

Note: Mean bias = 1.69 (0.79 with omission of Gauge 480).

hydrograph at Main Street compared to the traditional method of using Thiessen polygons to spatially assign rainfall totals from the six local rain gauges. Due to two days of antecedent rainfall, losses were assumed to be negligible for this event. The two modeled outflow hydrographs from HEC-1 are plotted in Fig. 5 with the measured hydrograph from USGS Gauge 08075000 (HCOEM Gauge 420 in Fig. 1).

Both modeled hydrographs predicted the larger peak on October 18 very well, but did not do as well on the first peak. Using NEXRAD-estimated rainfalls, the model predicted the measured larger peak flow on October 18 within 4% of the observed peak flow, while the Thiessen polygon-estimated rainfall predicted the peak within about 8% of the observed peak flow. In addition, the radar model produced a slightly more accurate value of direct runoff and time of peak than the modeled values using the Thiessen polygons. A summary of the modeling results can be seen in Table 6. A comparison of the direct runoff (minus the baseflow from the two days of antecedent rainfall) and the basin average rainfall for the NEXRAD showed almost identical numbers, indicating that assumption of using zero losses was valid.

Because the October 1994 event was very complex, lasting over 40 h and producing a dual-peak hydrograph on Brays Bayou, two other smaller, single-peaked events were chosen to assess the applicability of using radar-estimated rainfall for



J. Hydrol. Eng. 2000.5:269-277.

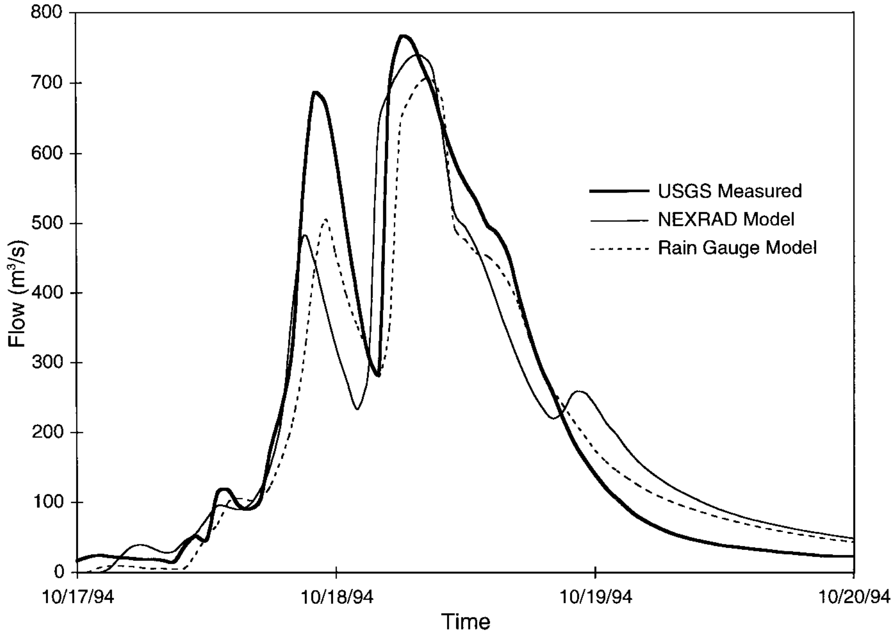


**FIG. 5. Comparison of Measured and Modeled Hydrographs at Main Street for October 1994 Storm**

**TABLE 6. Summary of Modeling Runs for Brays Bayou, October 1994**

| Observed and modeled hydrographs (1) | Direct runoff (cm) (2) | Peak flow ($m^3$/s) (3) | Time of peak (4) |
|---|---|---|---|
| Measured hydrograph at USGS 08075000 | 23.42 | 760 | October 18 6:30 a.m. |
| Modeled hydrograph using NEXRAD | 23.16 | 738 | October 18 7:30 a.m. |
| Modeled hydrograph using rain gauges | 21.51 | 704 | October 18 8:30 a.m. |

hydrologic modeling. Both events, the April 1997 and the January 1998, were chosen for analysis because they produced a single-peaked hydrograph response from a short, intense rainfall.

The hydrographs from the two modeling runs for the April 1997 storm, as well as the observed hydrograph at Main Street, are shown in Fig. 6. Because the mean bias for this storm was significant, it was expected that the NEXRAD-estimated hydrograph and the rain gauge-modeled hydrograph would be quite different. Examination of the outflow hydrographs indicates that NEXRAD-estimated rainfall closely matched the actual rainfall quite well compared to the gauge-estimated rainfall. Table 7 summarizes the modeling results.

Similar results were observed for the January 1998 storm event. The hydrographs from the two modeling runs, as well as the observed hydrograph at Main Street, are shown in Fig. 7 for the January 1998 storm. As with the April 1997 storm, the mean bias for the January 1998 storm was very large. Therefore, it was expected that the NEXRAD model hydrograph and the rain gauge model hydrograph would be quite different. Runoff volumes from the NEXRAD-estimated rainfall overpredicted the runoff volume from the streamflow gauge by 1.55 cm, a difference of 26%. The modeled direct runoff using gauge-estimated rainfall underestimated the mea-

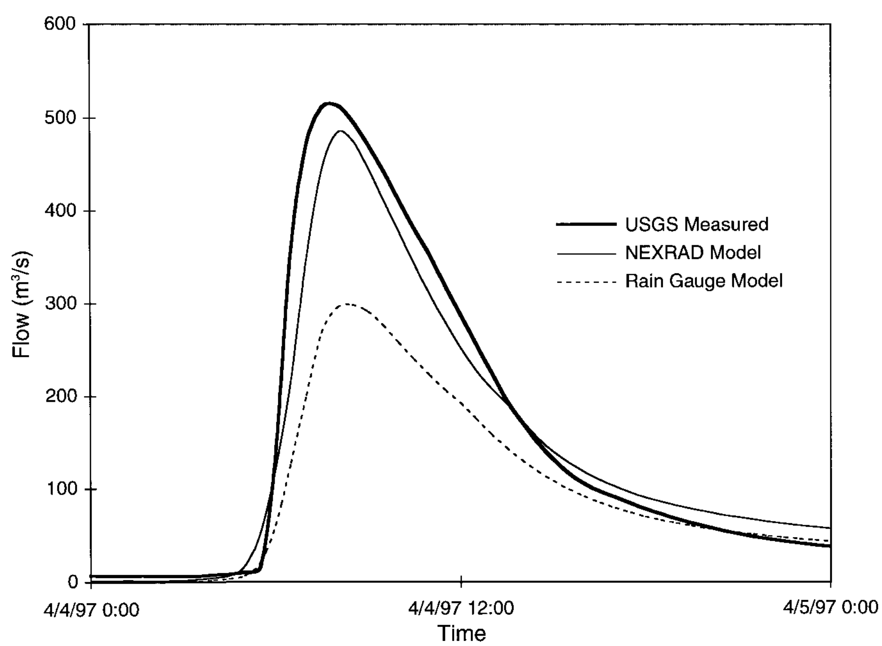


**FIG. 6. Comparison of Measured and Modeled Hydrographs at Main Street for April 1997 Storm**

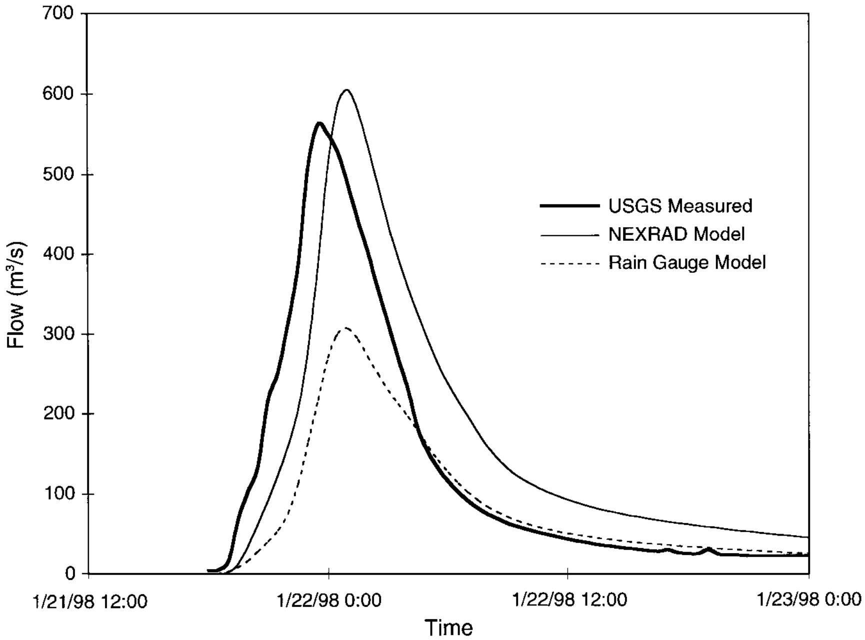


**FIG. 7. Comparison of Measured and Modeled Hydrographs at Main Street for January 1998 Storm**

**TABLE 7. Summary of Modeling Runs for Brays Bayou, April 1997**

| Observed and modeled hydrographs (1) | Direct runoff (cm) (2) | Peak flow ($m^3$/s) (3) | Time of peak (4) |
|---|---|---|---|
| Measured hydrograph at USGS 08075000 | 5.49 | 520 | April 4 7:45 a.m. |
| Modeled hydrograph using NEXRAD | 5.18 | 483 | April 4 8:00 a.m. |
| Modeled hydrograph using rain gauges | 3.56 | 298 | April 4 8:30 a.m. |

**TABLE 8. Summary of Modeling Runs for Brays Bayou, January 1998**

| Observed and modeled hydrographs (1) | Direct runoff (cm) (2) | Peak flow ($m^3$/s) (3) | Time of peak (4) |
|---|---|---|---|
| Measured hydrograph at USGS 08075000 | 6.04 | 560 | January 21 11:45 p.m. |
| Modeled hydrograph using NEXRAD | 7.59 | 605 | January 22 1:00 a.m. |
| Modeled hydrograph using rain gauges | 3.99 | 306 | January 22 1:00 a.m. |

sured direct runoff by 3.6 cm, a difference of 34%. A summary table of the modeling result can be seen in Table 8.

Results from the modeling runs from the smaller storms on Brays Bayou show that the NEXRAD-estimated rainfall better characterized the rainfall during the April 1997 and January 1998 events on Brays Bayou, despite large gauge-radar biases. For the April 1997 storm event, the NEXRAD-estimated peak flow and direct runoff differed by less than 7% from the measured values. The rain gauge network produced predicted values that differed by 35% from the measured value. The NEXRAD-estimated rainfall also produced a better time of peak than the model run using only the gauge-estimated rainfall.

The January 1998 event produced similar results. The predicted peak flow using the radar was within 8% of the measured peak flow, whereas the rain gauge model underestimated the peak flow by almost 50%. Direct runoff for the NEXRAD-estimated rainfall model overpredicted the measured peak flow by about 25%, but still performed better than the 34% error produced from the underprediction of the gauge-estimated rainfall model. Times of peaks of both models were off by 1:15. However, it is clear from the results that the rain gauges did not register some of the more intense rainfalls that the radar did measure for these two events.

## CONCLUSIONS

From the rainfall data collected and the hydrologic modeling runs evaluated as part of this study, conclusions can be drawn regarding NEXRAD's ability to accurately characterize rainfall distributions. The ultimate goal of this study on Brays Bayou was to create a flood prediction tool, and the results show that NEXRAD-estimated rainfall performs as well as or better than the gauge-estimated rainfall, despite large gauge-radar biases.

The study focused on the comparison between rainfall estimated from the rain gauge network versus the rainfall estimated from the NEXRAD using the unadjusted tropical $Z-R$ relationship. For the October 1994 storm, the radar predicted the direct runoff within 0.3 cm of measured data, while the rain gauges predicted the direct runoff within 1.9 cm. The NEXRAD-estimated rainfall also produced a peak flow within 4% and a time of peak within one hour of the observed peak flow, while the rain gauge-estimated rainfall produced a peak flow within 8% and a time of peak within two hours. For the October 1994 event, the NEXRAD-estimated rainfall model performed better than the rain gauge-estimated rainfall model.

Comparisons of two smaller events were made on Brays Bayou for the April 1997 and January 1998 storms. For both storms, the NEXRAD-estimated rainfall predicted the runoff volume by about 6% for the April 1997 storm and by about 26% for the January 1998 storm. The rain gauge data considerably underestimated the runoff volume by about 35% for the April 1997 storm and by about 34% for the January 1998 storm. Peak flows were also better predicted using the NEXRAD-estimated rainfall models versus the rain gauge models. Based on the sporadic nature of the data for these storms, there were pockets of intense rainfall that the gauge network simply missed, or there were some problems in the remote sensing of the rain gauge network, such as defective tipping buckets or data telemetering errors. Regardless, using only the rain gauge network, underprediction of the peak flow would have occurred.

For all three storm events analyzed, the model using the NEXRAD-estimated rainfall produced times of peaks as accurate or more accurate than the model using the gauge-estimated rainfall. This difference is critical for flood prediction and emergency response in a highly urbanized watershed that contains the Texas Medical Center and several major university campuses and museums within the Brays Bayou watershed.

The rain gauge network is vital in the comparison and continual calibration of the radar data. When used in conjunction with a fully operational gauging network, the NEXRAD radar has been shown to be as accurate as the gauged data, and in some cases, to increase the accuracy of rainfall prediction. In addition, the radar can also be used to reach out to hundreds of kilometers beyond the watershed boundary as storms approach the area. In this way, NEXRAD is being used as a valuable link in the creation of a flood warning system for the Brays Bayou watershed in Houston.

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