In cooperation with the Harris County Flood Control District
and the City of Houston

Effects of Urban Development on Stormwater Runoff Characteristics for the Houston, Texas, Metropolitan Area

Water-Resources Investigations Report 01–4071

U.S. Department of the Interior
U.S. Geological Survey

Cover:

Severe flooding in Houston, June 2001 (photograph courtesy of the *Houston Chronicle*).

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By Fred Liscum

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In cooperation with the Harris County Flood Control District
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Sea Level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Effects of Urban Development on Stormwater Runoff Characteristics for the Houston, Texas, Metropolitan Area

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Abstract

A study was done to estimate the effects of urban development in the Houston, Texas, metropolitan area on nine stormwater runoff characteristics. Three of the nine characteristics define the magnitude of stormwater runoff, and the remaining six characteristics describe the shape and duration of a storm hydrograph. Multiple linear regression was used to develop equations to estimate the nine stormwater runoff characteristics from basin and rainfall characteristics. Five basin characteristics and five rainfall characteristics were tested in the regressions to determine which basin and rainfall characteristics significantly affect stormwater runoff characteristics. Basin development factor was found to be significant in equations for eight of the nine stormwater runoff characteristics. Two sets of equations were developed, one for each of two regions based on soil type, from a database containing 1,089 storm discharge hydrographs for 42 sites compiled during 1964–89.

The effects of urban development on the eight stormwater runoff characteristics were quantified by varying basin development factor in the equations and recomputing the stormwater runoff characteristics. The largest observed increase in basin development factor for region 1 (north of Buffalo Bayou) during the study resulted in corresponding increases in the characteristics that define magnitude of stormwater runoff ranging from about 40 percent (for direct runoff) to 235 percent (for peak yield); and corresponding decreases in the characteristics that describe hydrograph shape and duration ranging from about 22 percent (for direct runoff duration) to about 58 percent (for basin lag). The largest observed increase in basin development factor for region 2 (south of Buffalo Bayou) during the study resulted in corresponding increases in the characteristics that define magnitude of stormwater runoff ranging from about 33 percent (for direct runoff) to about 210 percent (for both peak flow and peak yield); and corresponding decreases in the characteristics that describe hydrograph shape and duration ranging from about 38 percent (for direct runoff duration) to about 64 percent (for basin lag).

INTRODUCTION

The Houston, Texas, metropolitan area (fig. 1) has been undergoing extensive urban development since the 1950s. The U.S. Geological Survey (USGS), in cooperation with the Harris County Flood Control District and the City of Houston, began the continuing Houston Urban Runoff Program (HURP) in 1964 to define the magnitude and frequency of floods; to document variations in streamwater quality for different flow conditions, seasons, and types of urban development; and to determine the effects of urban development on stormwater runoff characteristics. A previous report presented data defining the magnitude of floods and the water-quality data available for the Houston area (Liscum and others, 1996).

Stormwater runoff can be quantified from a storm discharge hydrograph, a continuous graph of instantaneous stream discharge versus time for a storm. Stormwater runoff characteristics define or describe the magnitude, shape, and duration of a storm discharge hydrograph. Stormwater runoff characteristics are related to drainage basin and storm rainfall characteristics. If the relations between stormwater runoff characteristics and associated basin and rainfall characteristics can be established, then the stormwater runoff characteristics that are measurably affected by urban development, and how they are affected, can be determined. Such information can be used by water-resource

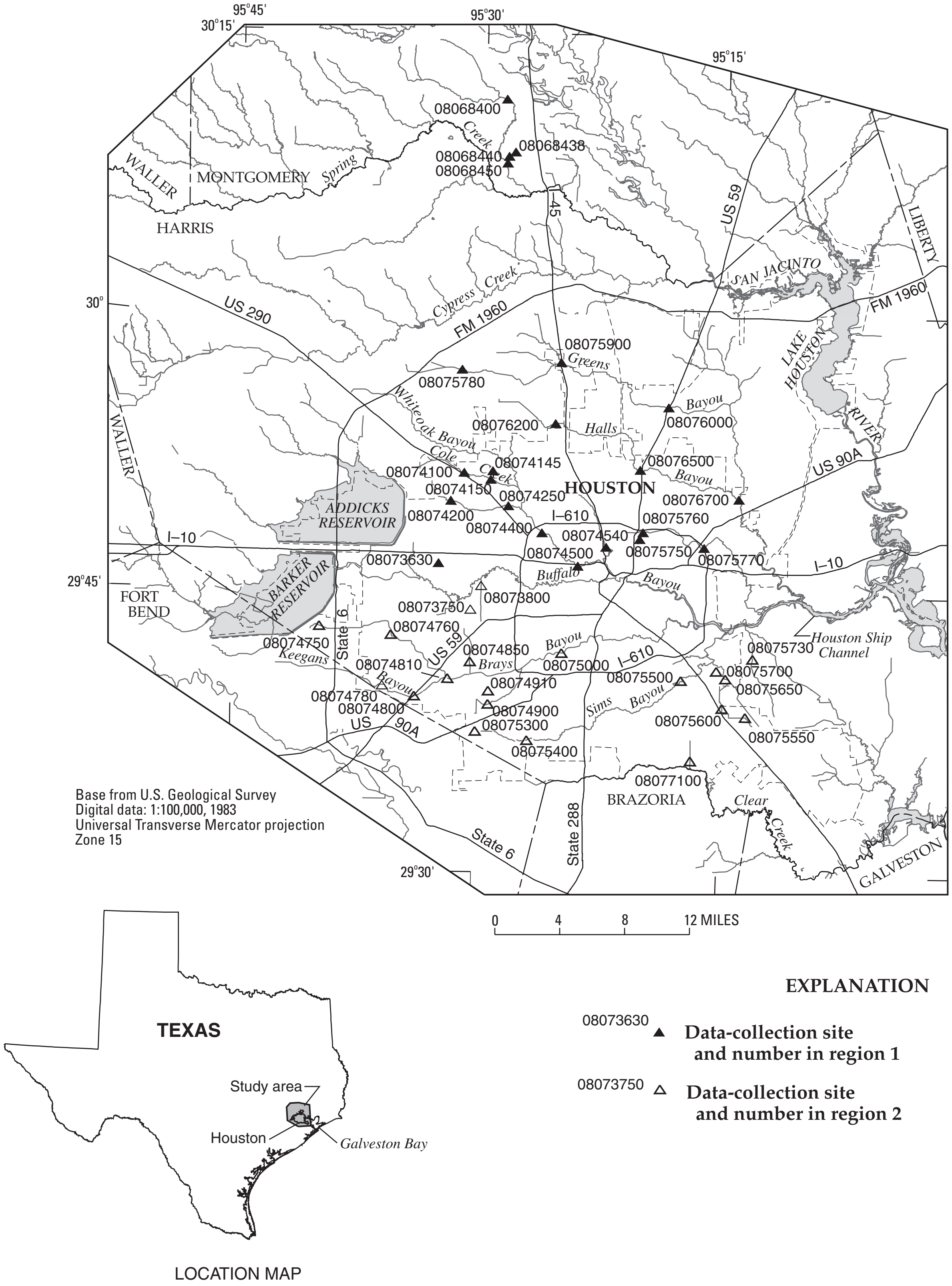

Figure 1. Location of study area and data-collection sites.

managers to estimate storm runoff characteristics—for example, peak discharge for a given level of development in a basin for a given rainfall event.

Past studies have identified the effects of urban development on the computed flood peak for selected probabilities of occurrence such as recurrence intervals of 2 to 500 years (Johnson and Sayre, 1973; Liscum and Massey, 1980). However, as those studies emphasize, the analysis of surface-water runoff in an urban coastal environment such as Houston is complicated by limitations imposed on the runoff process by the nearly flat topography and the interactions of urban development with the nearly flat topography.

A study was conducted by the USGS, in cooperation with the Harris County Flood Control District and the City of Houston, to estimate the effects of urban development on stormwater runoff characteristics in the Houston metropolitan area. Nine stormwater runoff characteristics were selected for study. Multiple linear regression was used to develop equations to estimate the nine stormwater runoff characteristics. Five basin characteristics and five rainfall characteristics were selected as independent variables and tested in the regressions to determine which basin and rainfall characteristics significantly affect stormwater runoff characteristics. The effects of urban development on the stormwater runoff characteristics were quantified by varying the significant basin characteristic that accounts for urban development in the regression equations and recomputing the stormwater runoff characteristics. Two sets of equations were developed, one for each of two regions based on soil type. The purpose of this report is to present the results of the study.

Data collected for the HURP during 1964–89 were used in this study. A total of 1,089 storm-discharge hydrographs from 42 sites (fig. 1; table 1) were available for analysis (Liscum and others, 1996).

Description of Study Area

The Houston metropolitan area is in southeastern Texas about 45 miles northwest of the Gulf of Mexico on an almost level plain. Land-surface altitudes in the study area range from 35 feet above sea level in the southeastern part to 135 feet in the northwestern part. Soils are predominately clay, clay loams, and fine sandy loams of low permeability. The Houston metropolitan area developed rapidly during 1964–89. Population increased from 1.42 million in 1960 to 3.30 million in 1990 (A.H. Belo Corp., 1991).

The major stream draining the study area is Buffalo Bayou (fig. 1), a tributary of the San Jacinto River. Buffalo Bayou has been regulated by Barker and Addicks (flood-detention) Reservoirs in the western part of the area since the late 1940s. From these reservoirs, Buffalo Bayou meanders eastward, is fed by four major tributaries (Whiteoak, Brays, Sims, and Greens Bayous), and enters the Houston Ship Channel and then Galveston Bay on the Gulf of Mexico. The drainage area of Buffalo Bayou, excluding the area upstream of the reservoirs, is about 810 square miles.

The climate of the Houston metropolitan area is characterized by short mild winters, long hot summers, high relative humidity, and prevailing southeasterly winds. The 30-year (1961–90) average annual rainfall for Houston is 46.1 inches, which is distributed uniformly throughout the year (Ramos, 1997).

Acknowledgments

The USGS acknowledges the support of agencies who participated in this study. Principal among those are the Harris County Flood Control District and the City of Houston. The U.S. Army Corps of Engineers also provided support for parts of the study.

EQUATIONS FOR ESTIMATING EFFECTS OF URBAN DEVELOPMENT ON STORMWATER RUNOFF CHARACTERISTICS

The effects of urban development on nine stormwater runoff characteristics (table 2) in the Houston metropolitan area were estimated from regression equations. Stormwater runoff characteristics are functions of selected basin and rainfall characteristics in the regression equations. Stormwater runoff characteristics define or describe the magnitude, shape, and duration of a storm discharge hydrograph (fig. 2). Basin characteristics affect the hydrologic responses of a watershed. Rainfall characteristics define the magnitude and duration of the rainfall that produces the storm runoff.

Stormwater Runoff Characteristics

The stormwater runoff characteristics used to develop the regression equations were computed from the available storm discharge hydrographs (table 3). Peak flow (QPEAK), peak yield (YPEAK) (ratio of QPEAK to drainage area), and direct runoff (ROVOL) define the magnitude of stormwater runoff. An analysis

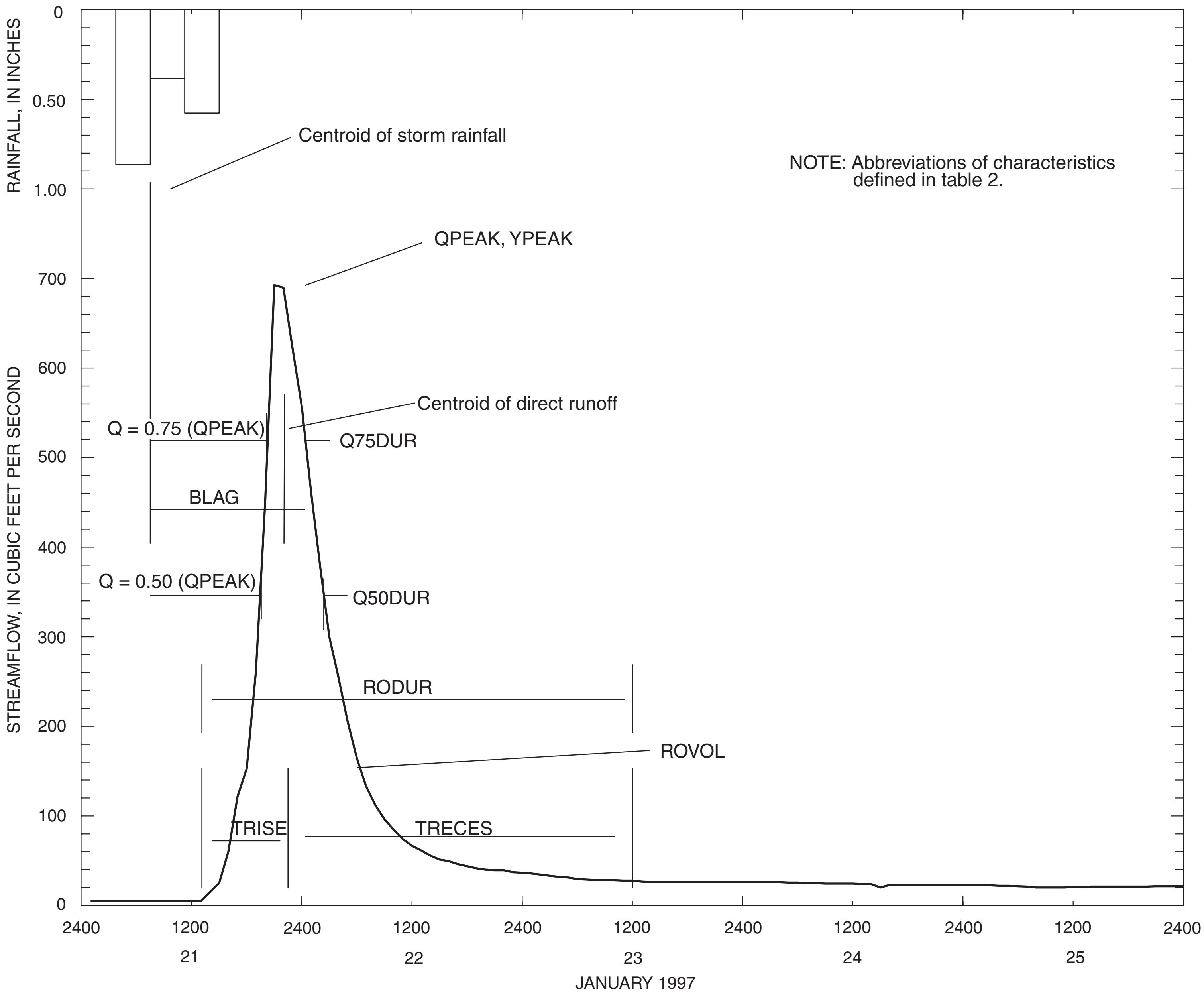

Figure 2. Storm discharge hydrograph showing stormwater runoff characteristics.

Table 1. Data-collection sites in the study area

USGS station no.	Region	Station name	Latitude	Longitude
08068400	1	Panther Branch near Conroe, Tex.	30°11'28"	95°28'44"
08068438	1	Swale No. 8 at Woodlands, Tex.	30°08'38"	95°28'09"
08068440	1	Lake Harrison at Drop Inlet at Woodlands, Tex.	30°08'24"	95°28'33"
08068450	1	Panther Branch near Spring, Tex.	30°08'02"	95°28'38"
08073630	1	Bettina St. Ditch at Houston, Tex.	29°46'32"	95°32'23"
08073750	2	Stoney Brook St. Ditch at Houston, Tex.	29°44'05"	95°30'22"
08073800	2	Bering Ditch at Woodway Dr., Houston, Tex.	29°45'22"	95°29'44"
08074100	1	Cole Creek at Guhn Rd. at Houston, Tex.	29°51'24"	95°30'55"
08074145	1	Bingle Rd. Storm Sewer at Houston, Tex.	29°51'31"	95°29'09"
08074150	1	Cole Creek at Deihl Rd., Houston, Tex.	29°51'04"	95°29'16"
08074200	1	Brickhouse Gully at Clarblak St., Houston, Tex.	29°49'53"	95°31'42"
08074250	1	Brickhouse Gully at Costa Rica St., Houston, Tex.	29°49'40"	95°28'09"
08074400	1	Lazybrook St. Storm Sewer at Houston, Tex.	29°48'15"	95°26'04"
08074500	1	Whiteoak Bayou at Houston, Tex.	29°46'30"	95°23'49"
08074540	1	Little Whiteoak Bayou at Trimble St., Houston, Tex.	29°47'33"	95°22'06"
08074750	2	Brays Bayou at Addicks-Clodine Rd., Houston, Tex.	29°43'02"	95°39'38"
08074760	2	Brays Bayou at Alief Rd., Alief, Tex.	29°42'39"	95°35'13"
08074780	2	Keegans Bayou at Keegan Rd. near Houston, Tex.	29°39'55"	95°35'42"
08074800	2	Keegans Bayou at Roark Rd. near Houston, Tex.	29°39'23"	95°33'43"
08074810	2	Brays Bayou at Gessner Dr., Houston, Tex.	29°40'21"	95°31'41"
08074850	2	Bintliff Ditch at Bissonnet St., Houston, Tex.	29°41'16"	95°30'20"
08074900	2	Willow Waterhole Bayou at Landsdowne St., Houston, Tex.	29°39'01"	95°29'11"
08074910	2	Hummingbird St. Ditch at Houston, Tex.	29°39'44"	95°29'11"
08075000	2	Brays Bayou at Houston, Tex.	29°41'49"	95°24'43"
08075300	2	Sims Bayou at Carlsbad St., Houston, Tex.	29°37'33"	95°29'56"
08075400	2	Sims Bayou at Hiram Clarke St., Houston, Tex.	29°37'07"	95°26'45"
08075500	2	Sims Bayou at Houston, Tex.	29°40'27"	95°17'21"
08075550	2	Berry Bayou at Gilpin St. at Houston, Tex.	29°38'32"	95°13'22"
08075600	2	Berry Bayou Tributary at Globe St., Houston, Tex.	29°39'00"	95°14'48"
08075650	2	Berry Bayou at Forest Oaks St., Houston, Tex.	29°40'35"	95°14'37"
08075700	2	Berry Creek at Galveston Rd. at Houston, Tex.	29°40'59"	95°15'11"
08075730	2	Vince Bayou at Pasadena, Tex.	29°41'40"	95°12'58"
08075750	1	Hunting Bayou Tributary at Cavalcade St., Houston, Tex.	29°48'00"	95°20'02"
08075760	1	Hunting Bayou at Falls St. at Houston, Tex.	29°48'22"	95°19'50"
08075770	1	Hunting Bayou at I–610, Houston, Tex.	29°47'35"	95°16'04"
08075780	1	Greens Bayou at Cutten Rd. near Houston, Tex.	29°56'56"	95°31'10"
08075900	1	Greens Bayou at U.S. Hwy 75 near Houston, Tex.	29°57'24"	95°25'04"
08076000	1	Greens Bayou near Houston, Tex.	29°55'05"	95°18'24"
08076200	1	Halls Bayou at Deertrail St. at Houston, Tex.	29°54'07"	95°25'21"
08076500	1	Halls Bayou at Houston, Tex.	29°51'42"	95°20'05"
08076700	1	Greens Bayou at Ley Rd., Houston, Tex.	29°50'13"	95°13'59"
08077100	2	Clear Creek Tributary at Hall Rd., Houston, Tex.	29°36'09"	95°16'41"

Table 2. Stormwater runoff, basin, and rainfall characteristics

Stormwater runoff characteristics	Abbreviation	Units
Peak flow	QPEAK	cubic feet per second
Peak yield	YPEAK	cubic feet per second per square mile
Direct runoff	ROVOL	inches
ROVOL duration	RODUR	hours
Time of rise to QPEAK	TRISE	hours
Duration of flow that equals or exceeds 75 percent of QPEAK	Q75DUR	hours
Duration of flow that equals or exceeds 50 percent of QPEAK	Q50DUR	hours
Time of recession from QPEAK to base flow	TRECES	hours
Duration from centroid of storm rainfall to centroid of direct runoff (basin lag)	BLAG	hours

Basin characteristics	Abbreviation	Units
Drainage area	DA	square miles
Slope factor	SL	miles per (feet per mile)$^{0.5}$
Soil index	SI	inches per hour
Basin development factor	BDF	dimensionless
Percent area developed	PAD	percent

Rainfall characteristics	Abbreviation	Units
Total rainfall	RTOT	inches
Maximum 60-minute rainfall	R60MAX	inches
Rainfall duration	RDUR	hours
Shortest 85-percent RDUR	R85DUR	hours
Antecedent rainfall index	RI	inches

Table 3. Summary statistics for stormwater runoff, basin, and rainfall characteristics

[Abbreviations of characteristics defined in table 2; statistics based on 1,089 storm discharge hydrographs]

Variable (units)	Mean	Standard deviation	Minimum	25th percentile	50th percentile (median)	75th percentile	Maximum
Stormwater runoff characteristics							
QPEAK (cubic feet per second)	1,811	3,439	20.0	229.0	572.0	1,890	32,500
YPEAK (cubic feet per second per square mile)	121.3	144.7	4.48	38.78	75.37	146.0	1,231
ROVOL (inches)	1.61	1.61	.03	.56	.99	2.12	9.02
RODUR (hours)	62.68	37.45	4.80	35.00	58.30	86.80	228.5
TRISE (hours)	10.59	11.99	.30	3.00	7.30	14.00	88.00
Q75DUR (hours)	5.27	4.60	.20	2.00	3.80	7.00	33.00
Q50DUR (hours)	9.30	7.88	.30	3.50	7.30	13.00	62.00
TRECES (hours)	51.16	31.12	3.70	28.80	46.00	74.50	219.5
BLAG (hours)	10.68	7.54	.10	5.10	9.40	14.40	40.80
Basin characteristics							
DA (square miles)	20.91	31.87	.13	3.42	10.70	20.20	182.0
SL (miles per [feet per mile]$^{0.5}$)	2.92	2.72	.13	1.21	2.12	3.65	13.02
SI (inches per hour)	1.15	.87	.20	.20	1.30	2.00	2.00
BDF (dimensionless)	6.36	2.65	0	5.00	6.03	8.00	12
PAD (percent)	62.85	21.05	15.30	48.20	65.66	76.66	100
Rainfall characteristics							
RTOT (inches)	3.11	2.11	.25	1.72	2.35	3.87	12.25
R60MAX (inches)	1.65	.75	.18	1.11	1.56	2.00	4.90
RDUR (hours)	17.00	21.85	.30	4.00	9.50	20.80	208.50
R85DUR (hours)	7.27	9.67	.20	1.80	4.30	8.00	72.00
RI (inches)	1.26	.98	.05	.46	1.00	1.85	5.78

of a series of QPEAKs over time can aid in the design of bridges and channels in a watershed as well as in the assessment of damage caused by flooding in a watershed. YPEAK can be used to estimate QPEAK at ungaged stream sites for selected storms. ROVOL is the amount of direct runoff produced by a storm in a basin. ROVOL is computed from the storm discharge hydrograph by assuming that base flow during the storm ranges from the discharge just before the start of the rise to the discharge after the hydrograph recession when there is little or no change. Knowing ROVOL for storms can aid in designing detention structures to reduce flood damage.

The remaining six stormwater runoff characteristics describe the shape and duration of a discharge hydrograph. ROVOL duration (RODUR) is the time from when direct runoff begins (start of streamflow rise) to when discharge returns to base flow. RODUR can be considered the width of the direct runoff hydrograph, thereby providing an indication of how long a storm might affect a basin. Time of rise to QPEAK (TRISE) is an indicator of storm rainfall intensity and distribution and how efficiently and effectively a basin conveys runoff to the receiving stream. Duration of flow that equals or exceeds 75 percent of QPEAK (Q75DUR) and duration of flow that equals or exceeds 50 percent of QPEAK (Q50DUR) are indicators of the shape of the storm discharge hydrograph. Time of the recession from QPEAK to base flow (TRECES) indicates the efficiency of the basin drainage system. Basin lag (BLAG) also indicates basin drainage efficiency, as well the temporal relation between rainfall and storm runoff.

In general, increasing urban development could cause QPEAK, YPEAK, and ROVOL to increase and RODUR, TRISE, Q75DUR, Q50DUR, TRECES, and BLAG to decrease (Leopold, 1968; Bedient and Huber, 1988).

Basin and Rainfall Characteristics

For the HURP, two types of basin characteristics were obtained for each data-collection site (Liscum and others, 1996). The first type comprises general descriptors of the basin that do not vary appreciably with time (drainage area [DA], slope factor [SL] [ratio of basin length to the square root of channel slope], and soil index [SI]). The second type comprises two indices of urban development in the basin over time (basin development factor [BDF] and percent of urban development [PAD] [percent area developed]).

DA is all the contributing area upstream of a gaging station and might also include some part of the drainage system across a topographic divide (connected by a sewer or open ditch). Obvious areas of storage, whether natural or constructed, are excluded in the computation of DA. Generally, QPEAKs for a larger DA will be greater than QPEAKs for a smaller DA if all other factors are identical. SL has two components—basin length and channel slope. Basin length is the distance along the channel from the streamflow-gaging station to the head of the basin, and channel slope is the slope between points at 10 percent and 85 percent of the basin length. SL has a similar effect on QPEAK as DA and also is a measure of basin drainage properties. SI is the maximum permeability of the natural soil on the basis of soil survey maps of the U.S. Department of Agriculture, Natural Resources Conservation Service (formerly Soil Conservation Service) (Johnson and Sayre, 1973). SI was the basis for defining the two regions of the study area. SI for sites north of Buffalo Bayou (region 1) ranged from 1.30 to 2.00 inches per hour; SI for sites south of Buffalo Bayou (region 2) was 0.20 inch per hour.

BDF is an index of the prevalence of four drainage features—channel improvements, channel linings, storm sewers, and curb-and-gutter streets (Sauer and others, 1983). BDF can range from 0 to 12 for an entire basin. Each of the four drainage features is evaluated and assigned a value ranging from 0 (not prevalent) to 1 (prevalent) for each one-third of a basin. The sum of all values represents the BDF for the entire basin. A BDF of zero indicates that the four drainage features are not prevalent but does not necessarily mean that the basin is not partially urbanized. A BDF of 12 indicates full development of the drainage features throughout the basin. BDF was used on a reverse scale (13 minus BDF) in the regression equations because Sauer and others (1983) found that doing so improved the linearity of regression equations and reduced the standard error of regression.

PAD is defined as the percentage of the total contributing DA within 200 feet of streets, roads, parking lots, and industrial sites that is drained by open ditches or storm sewers. PAD also includes roads in rural areas. PAD is highly correlated with the percentage of impervious area (Johnson and Sayre, 1973). For this reason, and the fact that PAD is easier than impervious area to estimate accurately from aerial photographs and other easily obtained maps, Liscum and Massey (1980) used PAD in previous work. Also, Southard (1986) confirmed that PAD was highly correlated with percent impervious area. PAD ranged from 15.30 to 100 percent for the Houston sites (table 3).

One measure of urban development in a basin, the amount of constructed detention storage (which likely lessens the effects of urban development on stormwater runoff characteristics), is not represented in the database for this study. Constructed detention storage to reduce stormwater runoff was implemented in the Houston metropolitan area in the early-to-mid 1980s. Constructed detention storage probably did not have an appreciable effect on stormwater runoff characteristics associated with the storm discharge hydrographs in the database of this study. On average, fewer hydrographs in the database are from the late 1980s than from the earlier (pre-detention-storage) years. Also, a time lag is likely between the time when constructed detention storage was implemented and when a sufficient amount of detention storage was constructed to measurably affect stormwater runoff characteristics.

BDF and PAD were computed three times for the study—for 1966, 1976, and 1984. These indices were computed for each of the 1966–84 storms by assuming linear change between 1966, 1976, and 1984. For pre-1966 and post-1984 storms, 1966 and 1984 values, respectively, were used. Variation in BDF and PAD ranged from little to no change in urban basins near downtown Houston, such as Hunting Bayou in region 1 (stations 08075750, 08075760, and 08075770) and Berry Bayou in region 2 (stations 08075550, 08075600, and 08075650), to large changes in basins that are distant from downtown Houston, such as Greens Bayou in region 1 (stations 08075780, 08075900, and 08076000) and Keegans Bayou in region 2 (stations 08074780 and 08074800). Figure 3 shows variation in BDF and PAD for four of these stations (08074800, 08075550, 08075770, and 08075900).

Three types of rainfall characteristics were determined for each storm at each site: (1) two measures of the rainfall amount for the storm—total rainfall (RTOT) and maximum 60-minute rainfall (R60MAX) (the maximum amount of rainfall in 60 minutes); (2) two measures of the duration of storm rainfall—rainfall duration (RDUR) and 85-percent duration (R85DUR) (the shortest time in which 85 percent of the rainfall occurred); and (3) antecedent rainfall index (RI) (a measure of the antecedent soil-moisture conditions). RTOT is the total amount of water potentially available for runoff. R60MAX indicates the intensity of rainfall for a storm. RDUR is the difference between the time when rainfall starts to when rainfall stops. RDUR indicates the type of storm—small RDURs are associated with thunderstorms and large RDURs with slower moving storms. R85DUR is another measure of storm duration and intensity. RI is defined by a relation that assumes soil moisture decreases logarithmically with time during periods of no rainfall—

$$RI_t = RI_0 * k^t, \qquad (1)$$

where

RI_0 is the initial value of the index (in inches),

RI_t is the reduced value of the index t days later (in inches), and

k is a recession factor set to 0.90 for this study (Linsley and others, 1982).

The index for any day is equal to that for the previous day multiplied by k. If rainfall occurs on any day, the amount is added to the index for that day.

Regression Analysis

Multiple linear regression was used to develop equations that relate stormwater runoff characteristics (the dependent variables) to significant basin and rainfall characteristics (the independent variables) for 42 sites in the two regions of the study area. Logarithmic (base 10) transformation of the variables was done to enhance the linearity of the equations. A multiple stepwise regression was done for each dependent variable in which independent variables were added one at a time (forward stepping) to obtain the final equation. The goal of the stepwise procedure is to ensure that only statistically significant independent variables are added to an equation and to exclude the variables that account for a very small part of the variance in the dependent variable (P–STAT, Inc., 1989). The intent of the procedure was to produce the “best” (as much of the variance in a dependent variable as possible explained with a small number of independent variables) equations to predict the selected stormwater runoff characteristics. Each equation was limited to no more than four independent variables—the four most significant. Independent variables that were highly correlated (correlation coefficient greater than 0.75) with each other were not included in an equation. Finally, each equation for a dependent variable was evaluated by considering the coefficient of

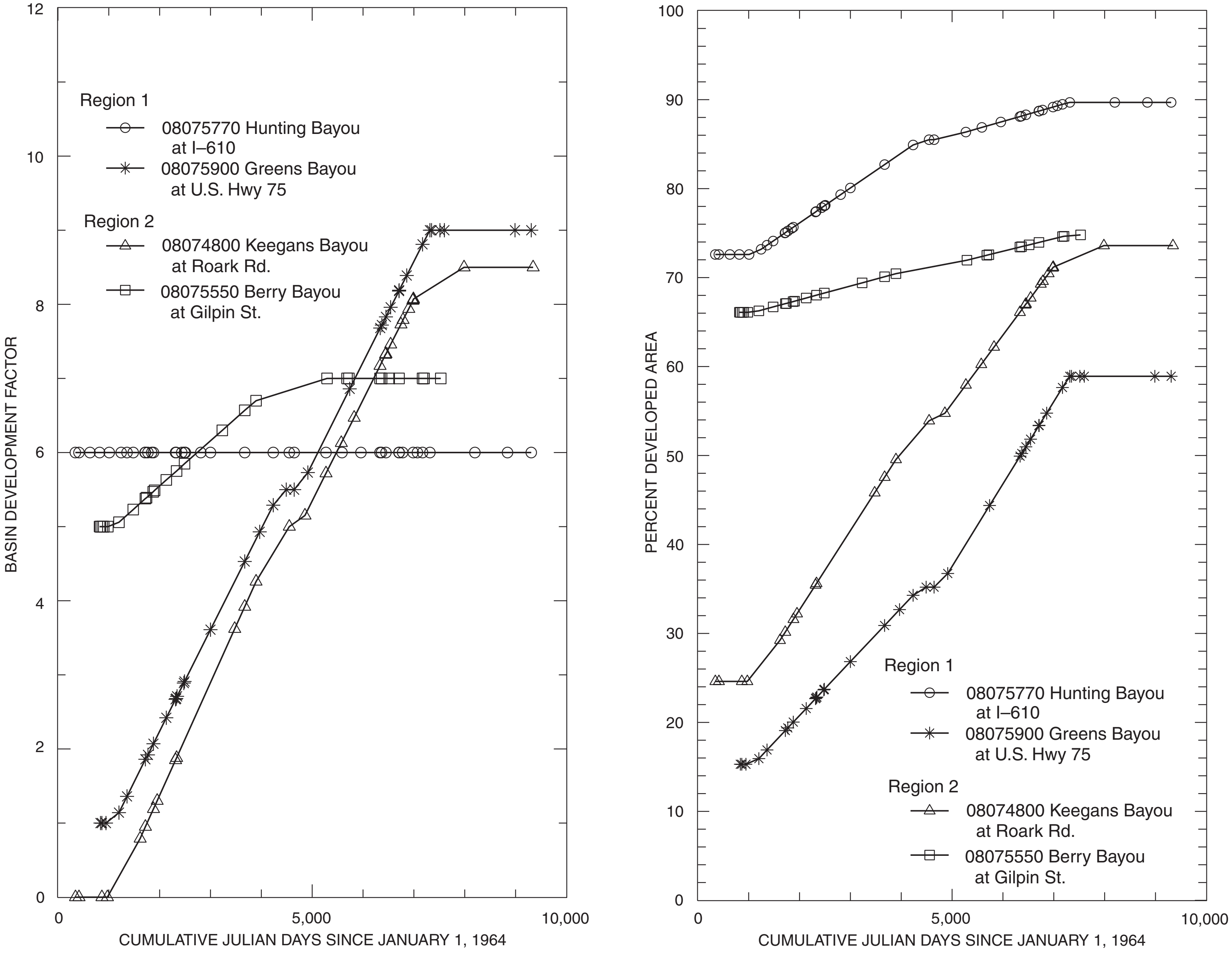

Figure 3. Changes in indices of urban development with time for sites reflecting the smallest and largest increases in urban development during 1964–89.

Table 4. Regression equations for estimating selected stormwater runoff characteristics

[Abbreviations of characteristics defined in table 2; R^2, coefficient of determination]

Region	Equation	R^2 (percent)	Standard error of regression (percent)	Standard error of regression (log 10 units)	No. of storms equation based on
Characteristics that define magnitude of stormwater runoff					
1	$QPEAK = 312\ DA^{0.728}\ (13 - BDF)^{-1.04}\ RTOT^{0.984}\ RI^{0.135}$	87	55	0.22	408
2	$QPEAK = 475\ DA^{0.735}\ (13 - BDF)^{-1.07}\ RTOT^{0.837}\ RI^{0.093}$	87	57	.23	331
1	$YPEAK = 243\ SL^{-0.410}\ (13 - BDF)^{-1.10}\ RTOT^{0.958}\ RI^{0.127}$	75	54	.22	408
2	$YPEAK = 475\ DA^{-0.265}\ (13 - BDF)^{-1.07}\ RTOT^{0.837}\ RI^{0.93}$	64	57	.23	331
1	$ROVOL = 0.403\ (13 - BDF)^{-0.303}\ RTOT^{1.30}\ RDUR^{0.081}\ RI^{0.205}$	73	56	.23	408
2	$ROVOL = 0.613\ (13 - BDF)^{-0.268}\ RTOT^{1.22}\ RI^{0.213}$	70	55	.22	331
Characteristics that describe shape and duration of discharge hydrograph					
1	$RODUR = 13.7\ DA^{0.199}\ (13 - BDF)^{0.227}\ RTOT^{0.298}\ R85DUR^{0.154}$	67	43	.18	408
2	$RODUR = 10.7\ SL^{0.410}\ (13 - BDF)^{0.439}\ RTOT^{0.274}\ R85DUR^{0.117}$	66	41	.17	331
1	$TRISE = 1.93\ DA^{0.199}\ RTOT^{0.741}\ R60MAX^{-0.519}\ R85DUR^{0.255}$	55	82	.31	408
2	$TRISE = 1.63\ DA^{0.278}\ RTOT^{0.501}\ R60MAX^{-0.357}\ R85DUR^{0.266}$	50	80	.31	331
1	$Q75DUR = 0.374\ DA^{0.294}\ (13 - BDF)^{0.678}\ RTOT^{0.678}\ R60MAX^{-0.425}$	77	52	.21	408
2	$Q75DUR = 0.367\ DA^{0.274}\ (13 - BDF)^{0.646}\ RTOT^{0.682}\ R60MAX^{-0.431}$	55	61	.25	331
1	$Q50DUR = 0.665\ DA^{0.287}\ (13 - BDF)^{0.723}\ RTOT^{0.625}\ R60MAX^{-0.454}$	80	47	.19	408
2	$Q50DUR = 0.624\ DA^{0.271}\ (13 - BDF)^{0.711}\ RTOT^{0.665}\ R60MAX^{-0.471}$	57	58	.23	331
1	$TRECES = 9.50\ DA^{0.223}\ (13 - BDF)^{0.337}\ RTOT^{0.282}\ R85DUR^{0.084}$	62	49	.20	408
2	$TRECES = 9.17\ SL^{0.435}\ (13 - BDF)^{0.473}\ RTOT^{0.314}\ RI^{0.091}$	58	48	.20	331
1	$BLAG = 0.720\ DA^{0.333}\ (13 - BDF)^{0.781}\ RTOT^{0.126}\ R85DUR^{0.106}$	77	52	.21	408
2	$BLAG = 0.693\ SL^{0.481}\ (13 - BDF)^{0.969}\ RTOT^{0.296}\ RI^{0.110}$	62	57	.23	331

determination[1] (R^2), standard error of regression[2], and residual (observed minus predicted values) plots.

The regression procedure thus comprised the following steps: (1) Compute the correlation coefficients between all independent variables. (2) Apply multiple stepwise regression to develop an equation for each dependent variable. (3) Inspect the resulting equations and remove independent variables that were highly correlated. Repeat step 2 without the highly correlated variables. (4) Examine R^2 and standard error of regression. Select the equation with the largest R^2 and the smallest standard error of regression. (5) Examine residual plots. Accept the equation if two criteria are met: First, a plot of residuals versus predicted values shows no discernible pattern, indicating constant variance as the predicted value increases; and second, a stem-and-leaf plot (Ott, 1993) shows symmetry about zero (lack of skewness), indicating that the residuals are normally distributed.

Regression Equations

The procedure described above was used to develop equations to estimate the nine selected stormwater runoff characteristics (table 4). R^2 ranged from

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[1] Coefficient of determination indicates the proportion of the total variation of the dependent variable that is explained by the independent variables (Sauer and others, 1983).

[2] Standard error of regression is one standard deviation on each side of the line defined by the regression equation and contains about two-thirds of the data (Sauer and others, 1983).

64 to 87 percent, and the standard error of regression ranged from 54 to 57 percent, for the characteristics that define the magnitude of stormwater runoff. R^2 ranged from 50 to 80 percent, and the standard error of regression ranged from 41 to 82 percent, for the characteristics that describe the shape and duration of the discharge hydrograph. BDF, the index of urban development, was significant for all but one of the nine runoff characteristics; the exception was TRISE.

The development of the equations is summarized by considering two of the characteristics, QPEAK and BLAG. QPEAK is representative of the characteristics that define the magnitude of storm runoff, and BLAG is representative of the characteristics that describe the shape and duration of a discharge hydrograph.

For both regions, QPEAK was found to be a function of DA, BDF, RTOT, and RI. The constants and exponents of the variables in the two equations are of similar magnitude. As the equations indicate, QPEAK increases as DA, RTOT, and RI increase. The equations confirm that increases in urban development, represented by increases in BDF, increase QPEAK. Graphs of predicted versus observed QPEAK for the two regions (fig. 4a) show reasonable agreement, as would be expected from the magnitude of R^2 (table 4), which indicates that the independent variables account for about 87 percent of the variance. The standard error of regression, in percent, indicates that about two-thirds of the observed QPEAKs are within plus or minus 57 percent of the corresponding predicted QPEAKs. Plots of QPEAK residuals versus predicted QPEAKs for the two regions (fig. 5a) show no discernible pattern; and stem-and-leaf plots of the residuals indicate no appreciable skewness (fig. 6a).

For region 1, BLAG was found to be a function of DA, BDF, RTOT, and R85DUR (table 4). For region 2, BLAG was found to be a function of SL, BDF, RTOT, and RI. The equations show that as DA, SL, RTOT, R85DUR, and RI increase, BLAG increases. This result is logical—an increase in any of these characteristics would result in more storm runoff and larger peak flows, which in turn would increase the time for runoff from the farthest reaches of the basin to exit the basin (another definition for BLAG). The equations also show that as BDF increases, BLAG decreases because a developed drainage system allows storm runoff to exit the basin more rapidly than an undeveloped drainage system. R^2 (62 to 77 percent) and standard error of regression (52 to 57 percent) indicate acceptable agreement between predicted and observed BLAGs (fig. 4b) (table 4). Plots of the residuals versus predicted BLAGs indicate no discernible pattern for either region (fig. 5b). Stem-and-leaf plots of the residuals indicate slight skew toward negative residuals and thus the potential for the equations to over-predict BLAG (fig. 6b); however, the distribution of the residuals appears to be near normal.

Limitations on Values for Basin and Rainfall Characteristics

Of the five basin and five rainfall characteristics selected as independent variables, the significant characteristics for the equations for each region are

Region 1: DA, SL, BDF, RTOT, R60MAX, RDUR, R85DUR, and RI;

Region 2: DA, SL, BDF, RTOT, R60MAX, R85DUR, and RI.

The equations can be used to estimate stormwater runoff characteristics not only for ungaged sites but also for different conditions at gaged sites, such as different levels of basin development and different rainfall events. However, the values for the independent variables should not exceed the ranges of values that were used to develop the equations (table 5). If values outside those ranges are used, the standard errors of regression likely will increase.

Evaluation of Regression Equations

The regression equations were evaluated on the basis of the standard error of regression between the observed and predicted values for the nine stormwater runoff characteristics and scatterplots of observed versus predicted values for the available storms for four sites—two drainage basins representative of those with the smallest increases in urban development during the study and two representative of those with the largest increases. As shown in figure 3, changes with time in BDF and PAD for region 1 streamflow-gaging station 08075770 (Hunting Bayou) and region 2 station 08075550 (Berry Bayou) range from none to moderate. Considerably larger changes with time in BDF and PAD are associated with region 1 station 08075900 (Greens Bayou) and region 2 station 08074800 (Keegans Bayou).

For the sites in both regions representing small increases in urban development (08075550 and 08075770), the standard errors of regression for QPEAK, YPEAK, and ROVOL (41 to 46 percent)

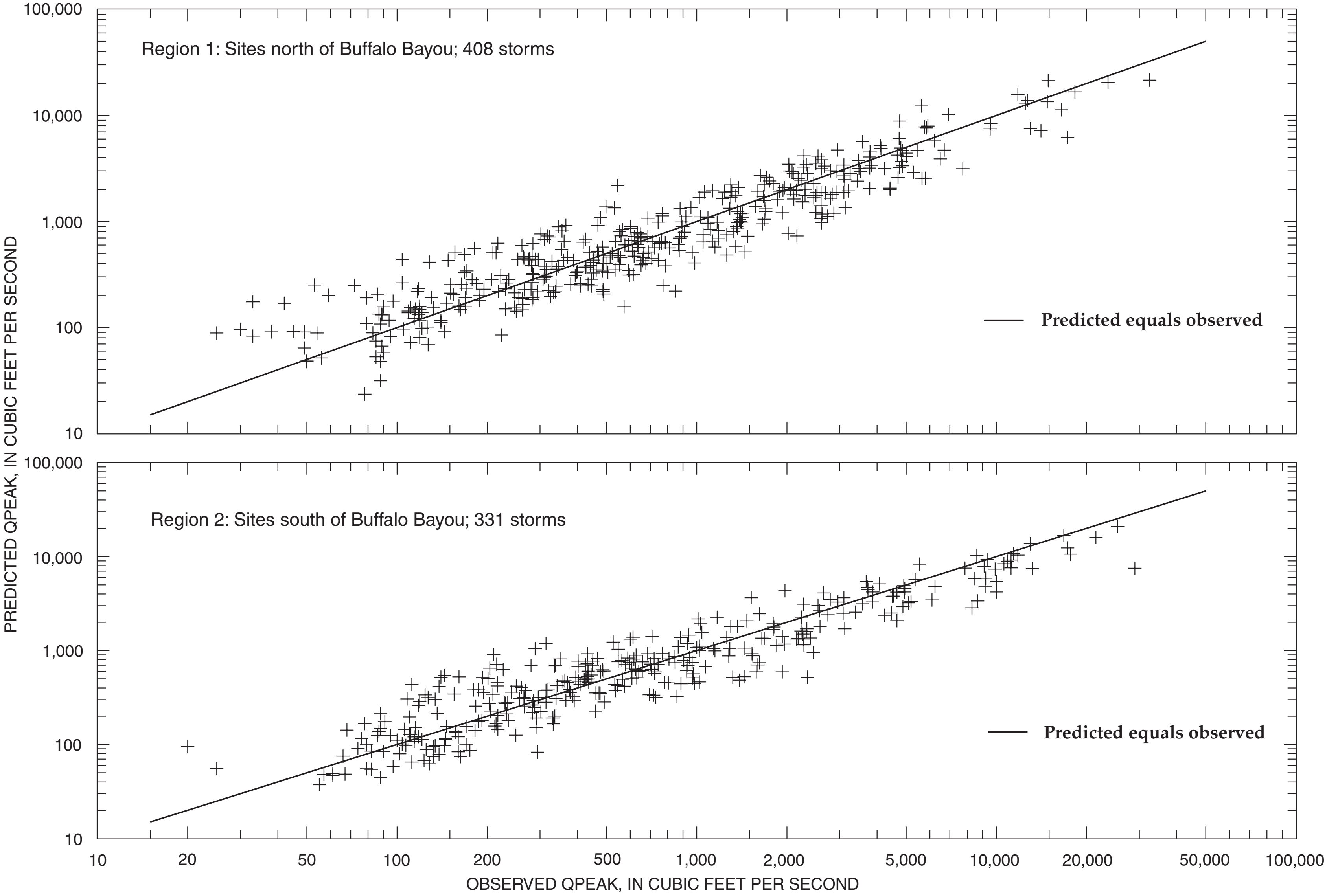

Figure 4a. Observed versus predicted peak flow (QPEAK) for all storms, by region.

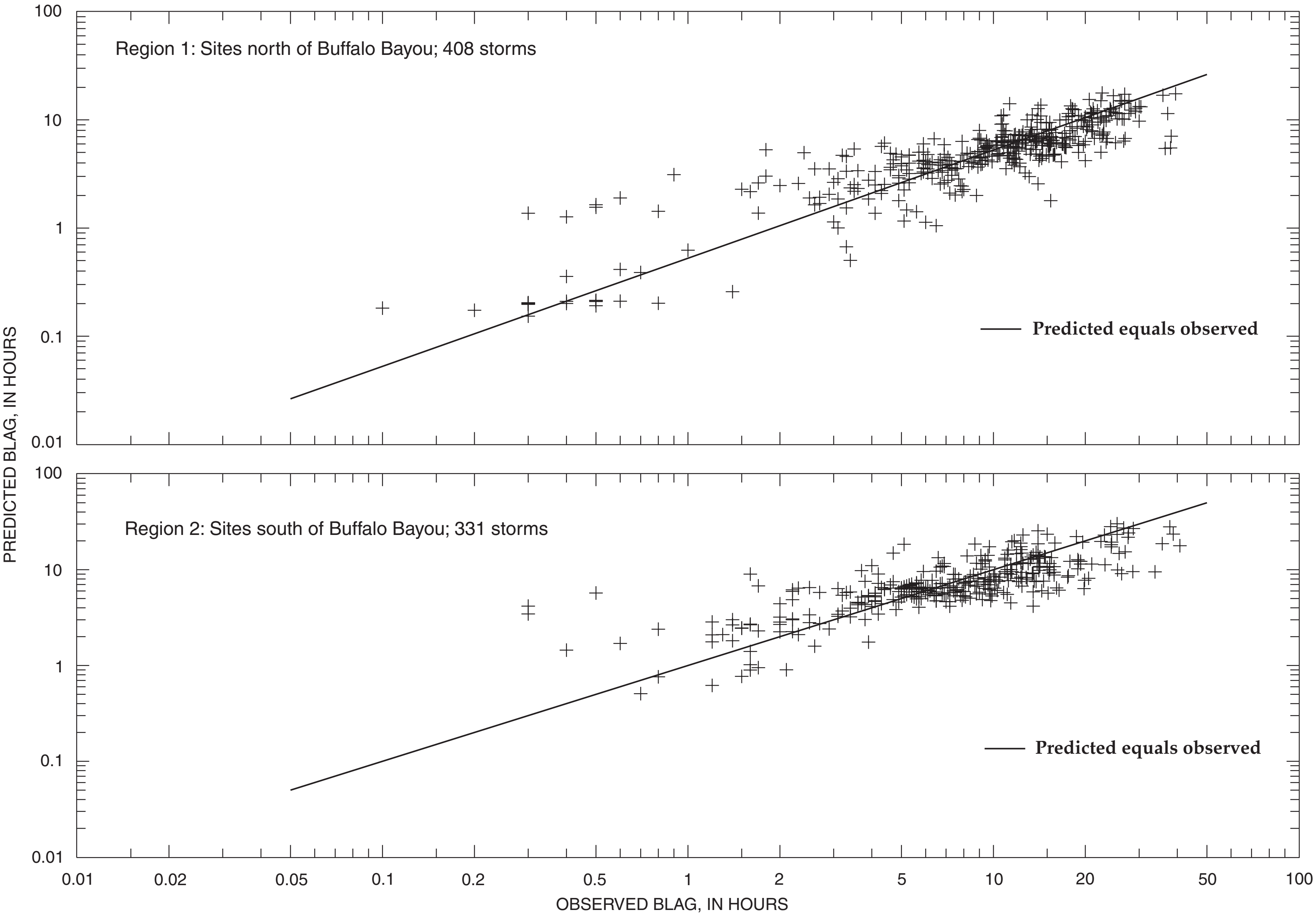

Figure 4b. Observed versus predicted basin lag (BLAG) for all storms, by region.

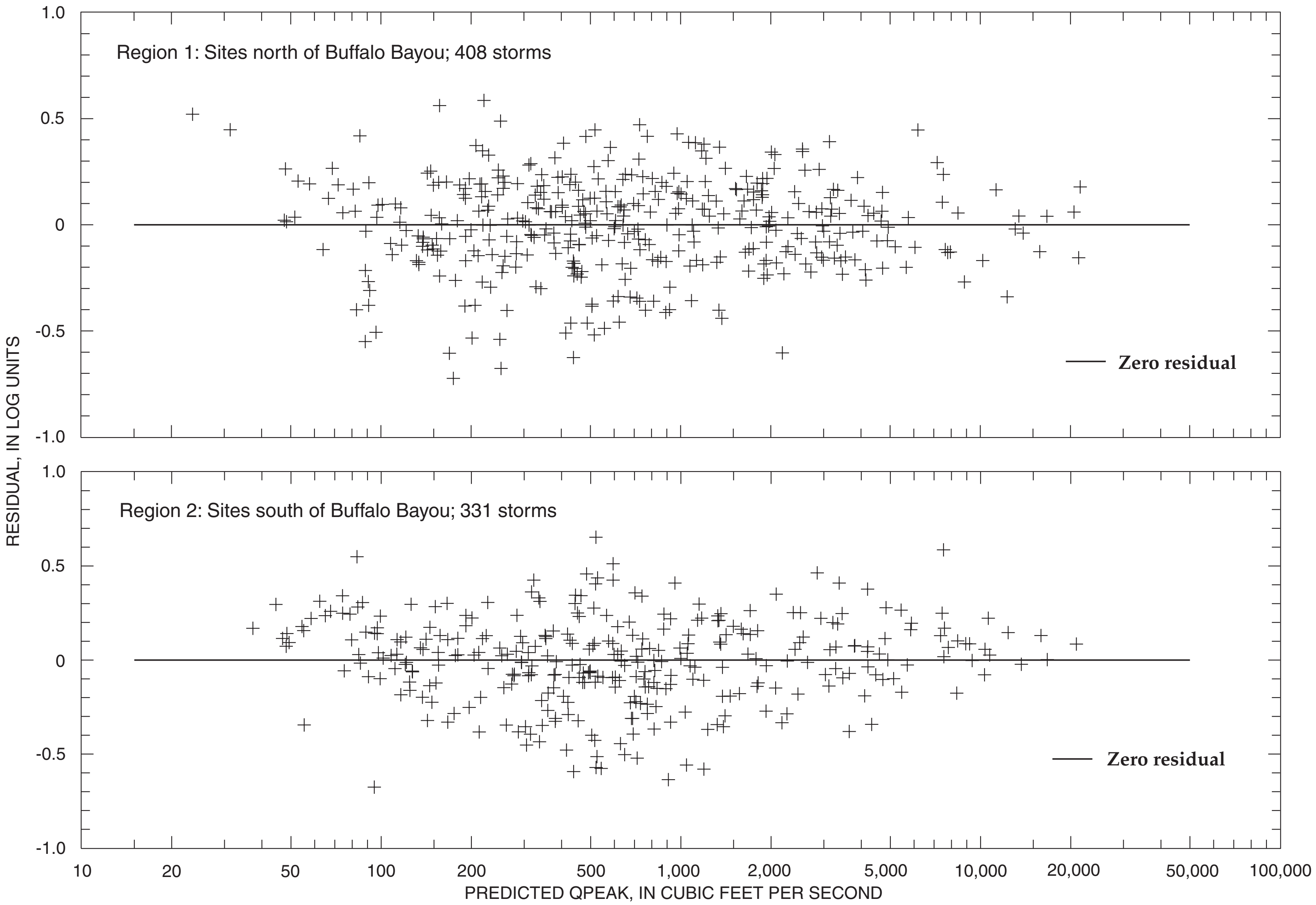

Figure 5a. Predicted values versus residuals for peak flow (QPEAK) for all storms, by region.

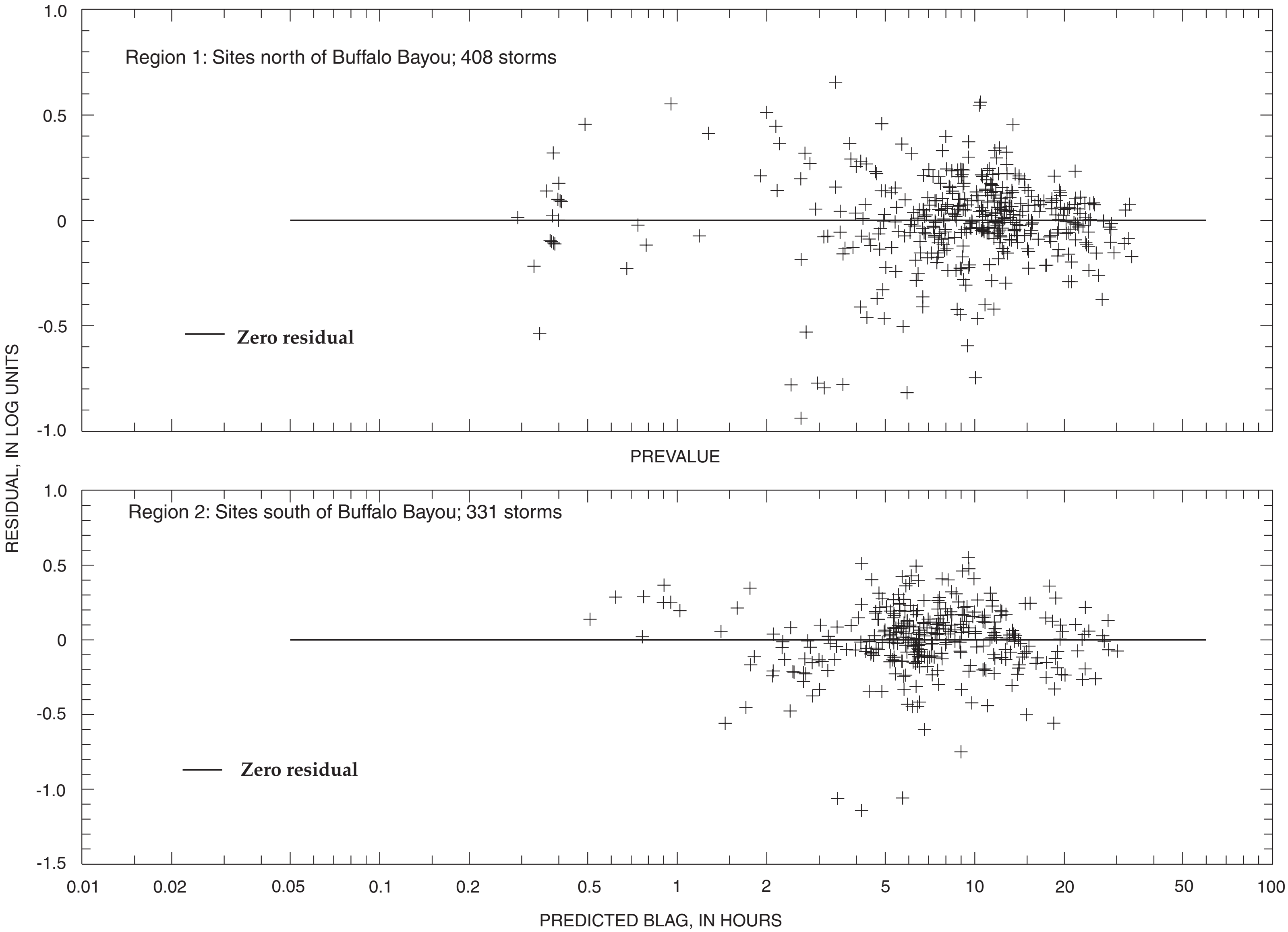

Figure 5b. Predicted values versus residuals for basin lag (BLAG) for all storms, by region.

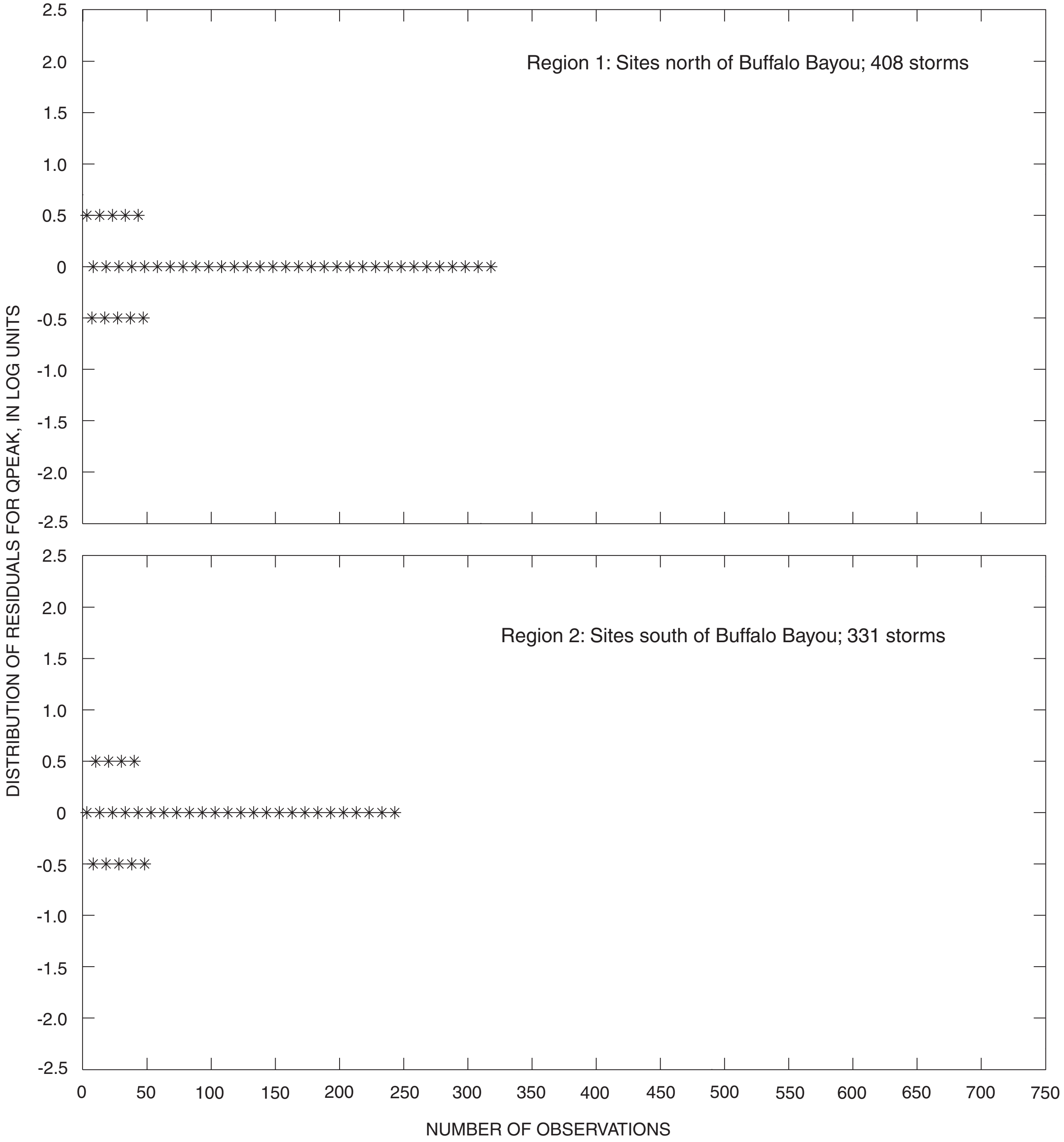

Figure 6a. Stem-and-leaf plots showing distribution of residuals for peak flow (QPEAK) for all storms, by region.

(table 6) are less than those based on all sites (54 to 57 percent) (table 4). For the sites in both regions representing large increases in urban development (08074800 and 08075900), standard errors for QPEAK and YPEAK (64 to 73 percent) are larger than those based on all sites; standard error for ROVOL is about the same (53 to 54 percent). On the basis of scatterplots of observed versus predicted values for the three characteristics (figs.7a–c at end of report), the regression equations produced reasonable results. The generally

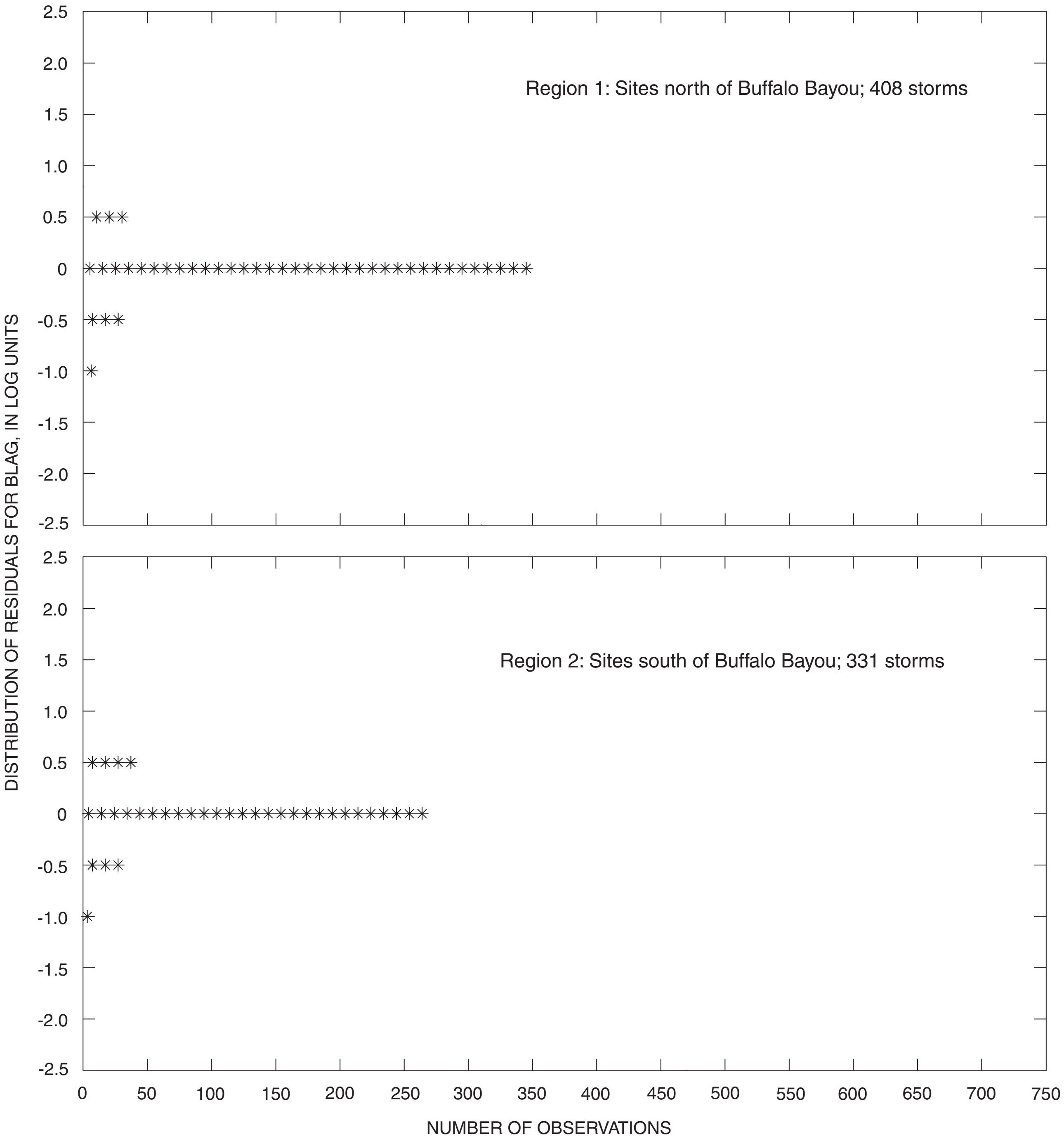

Figure 6b. Stem-and-leaf plots showing distribution of residuals for basin lag (BLAG) for all storms, by region.

larger standard errors of regression associated with the sites representing higher development rates are shown graphically by greater scatter of points about the predicted-equals-observed lines for sites 08074800 and 08075900 than for sites 08075550 and 08075770.

For the site in region 1 representing small increases in urban development (08075770), the standard errors of regression for the characteristics that define the shape and duration of a storm discharge hydrograph (RODUR, TRISE, Q75DUR, Q50DUR,

Table 5. Maximum and minimum values of independent variables used to develop regression equations

[Abbreviations of characteristics defined in table 2]

Independent variable (units)	Minimum	Maximum
Region 1: Sites north of Buffalo Bayou		
DA (square miles)	0.13	182
SL (miles per [feet per mile]$^{0.5}$)	.13	13.0
BDF (dimensionless)	0	12
RTOT (inches)	.42	10.9
R60MAX (inches)	.18	4.90
RDUR (hours)	.50	208.5
R85DUR (hours)	.20	72.0
RI (inches)	.05	5.76
Region 2: Sites south of Buffalo Bayou		
DA (square miles)	.32	94.9
SL (miles per [feet per mile]$^{0.5}$)	.25	8.74
BDF (dimensionless)	0	12
RTOT (inches)	.25	12.25
R60MAX (inches)	.25	3.91
R85DUR (hours)	.30	42.8
RI (inches)	.05	5.78

Table 6. Standard error of regression between observed and predicted stormwater runoff characteristics for available storms at selected sites representing small and large increases in urban development

[Abbreviations of characteristics defined in table 2; in percent]

Characteristic		Small increases in BDF		Large increases in BDF	
	Station no.:	08075770	08075550	08075900	08074800
	Region:	1	2	1	2
QPEAK		44	44	64	73
YPEAK		46	44	67	73
ROVOL		41	43	54	53
RODUR		29	28	36	35
TRISE		70	76	62	103
Q75DUR		37	64	40	80
Q50DUR		39	58	38	88
TRECES		34	40	44	37
BLAG		42	74	32	49

TRECES, and BLAG) averaged 42 percent, less than the average standard error for region 1 for all sites (54 percent). For the site in region 2 representing small increases in urban development (08075550), the standard errors of regression for those six characteristics averaged 57 percent, about the same as the average standard error for region 2 for all sites (58 percent). For the sites in regions 1 and 2 representing large increases in urban development, the standard errors of regression for the six characteristics averaged 42 and 65 percent, respectively. As with the characteristics that define the magnitude of stormwater runoff, the generally greater standard errors of regression for the equations that describe shape and duration associated with the sites representing larger development rates are shown graphically by greater scatter of points about the predicted-equals-observed lines for sites 08074800 and 08075900 than for sites 08075550 and 08075770 (figs. 7d–7i at end of report).

In general, the equations for stormwater runoff characteristics for the two sites representing small increases in urban development yielded smaller standard errors of regression than those for stormwater runoff characteristics for the two sites representing large increases in urban development. In general, standard errors of regression are smaller for the two region 1 sites than for the two region 2 sites (table 6).

Overall, the equations were judged acceptable. However, two potential sources of error are noted. First, the equations for QPEAK and YPEAK could yield inaccurate predicted values if the DAs used to develop the equations are too large; that is, if the entire drainage basin does not contribute to flow at the streamflow-gaging station. If the entire basin does not contribute to flow, SL could be inaccurate also. In this situation, the regression coefficients for DA, and possibly SL, would be inaccurate, and thus predicted QPEAKs and YPEAKs also would be inaccurate. Second, TRISE, Q75DUR, Q50DUR, and BLAG could be predicted inaccurately if the entire drainage basin does not contribute to flow at the streamflow-gaging station. The likelihood of an entire basin not contributing to flow is a function of storage in the basin. Natural storage is assumed to be accounted for in the database; however, constructed storage (detention ponds) for new development that was implemented in the Houston metropolitan area in the early-to-mid 1980s is not accounted for in the database. Constructed storage in a basin would decrease DA and could affect SL. A determination of the fraction of a basin that actually contributes to storm runoff or the amount of detention storage in the basin during a storm would increase the accuracy of all equations involving DA or SL.

EFFECTS OF URBAN DEVELOPMENT ON STORMWATER RUNOFF CHARACTERISTICS

The effects of urban development on stormwater runoff characteristics can be seen by comparing storm hydrographs from early in the program with those from the same sites later in the program. Little change in storm discharge hydrographs occurred during the program period for stations gaging stormwater runoff from basins where negligible to moderate urban development occurred, such as stations 08075770 and 08075550 (figs. 8a, c). However, the effect of urban development on stormwater runoff characteristics is apparent in hydrographs for stations gaging stormwater runoff from basins where substantial urban development occurred, such as stations 08075900 and 08074800 (figs. 8b, d).

All the equations for predicting stormwater runoff characteristics except the equation for TRISE include BDF as a significant variable. The other index to urban development, PAD, was not significant for any stormwater runoff characteristic (and also was correlated with BDF). Thus the effect of urban development in the equations is accounted for only by BDF.

Characteristics That Define Magnitude of Stormwater Runoff

QPEAK, YPEAK, and ROVOL define the magnitude of stormwater runoff. Increasing urban development increases the magnitude of each of these stormwater runoff characteristics, all other factors being equal. Storm hydrographs show that the magnitude of stormwater runoff changes only slightly for basins that have undergone only small increases in development (figs. 8a, c); however, storm hydrographs show much larger changes in the magnitude of stormwater runoff for basins that have undergone large increases in development (figs. 8b, d).

The effects of increases in urban development on QPEAK, YPEAK, and ROVOL were estimated from the equations by varying BDF in computations of the characteristics. The percent changes in QPEAK, YPEAK, and ROVOL depend not only on the range of change in development but also on the amount of beginning and ending development—that is, the beginning and ending values of BDF. The most extreme

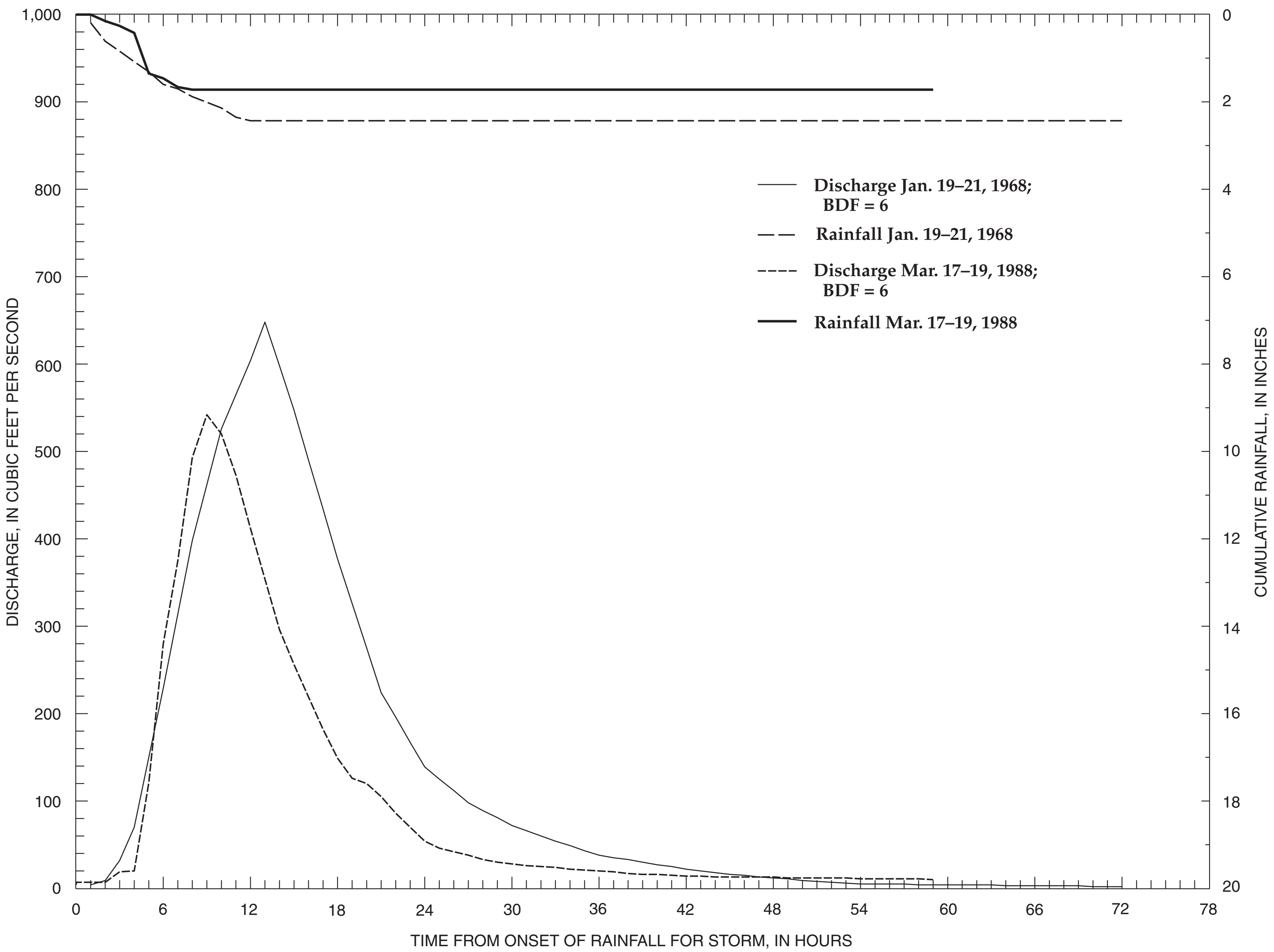

Figure 8a. Hydrograph for 080757770 Hunting Bayou at I–610 showing effects of no increase in basin development factor (BDF).

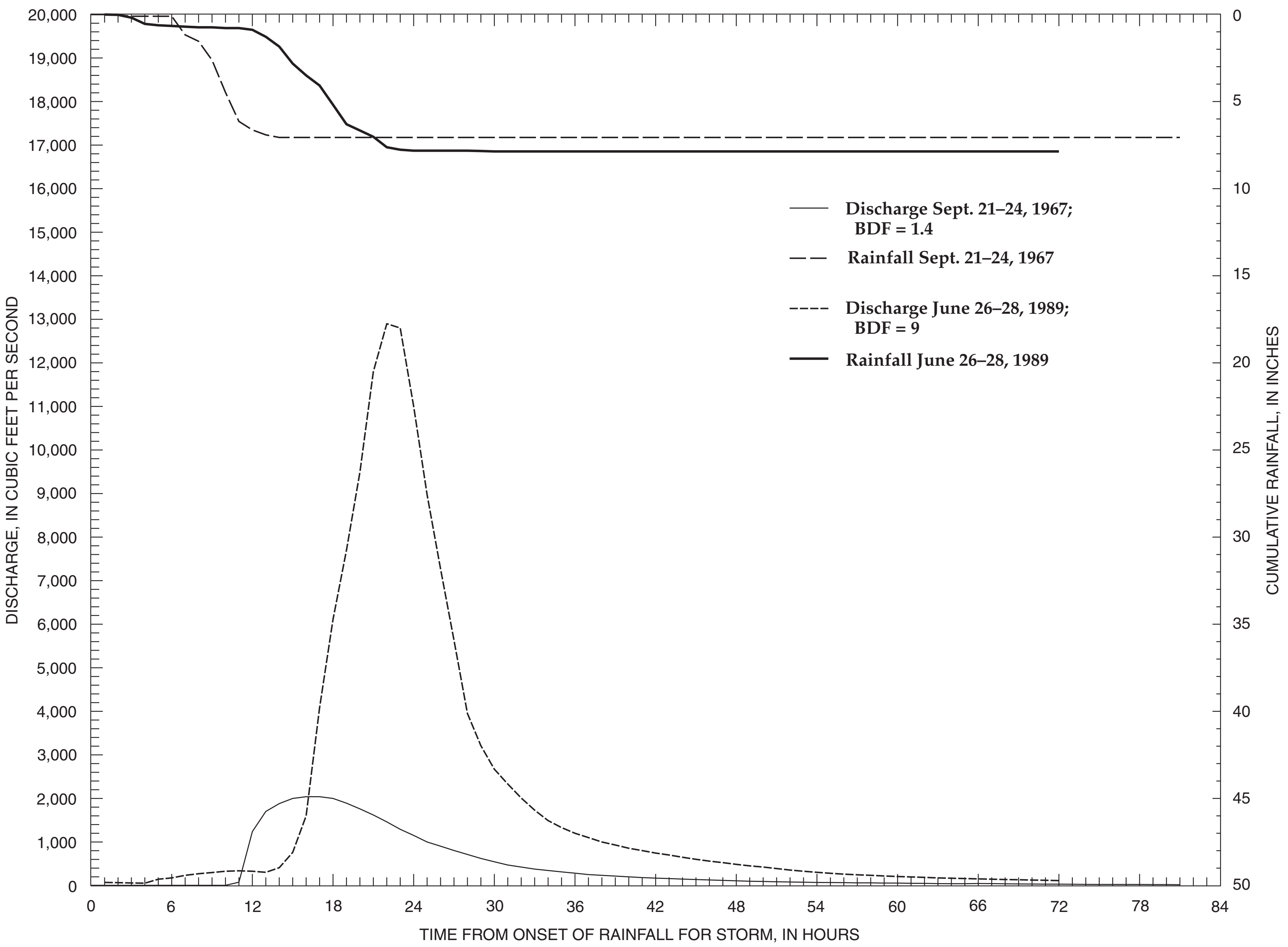

Figure 8b. Hydrograph for 08075900 Greens Bayou at U.S. Hwy 75 showing effects of large increase in basin development factor (BDF).

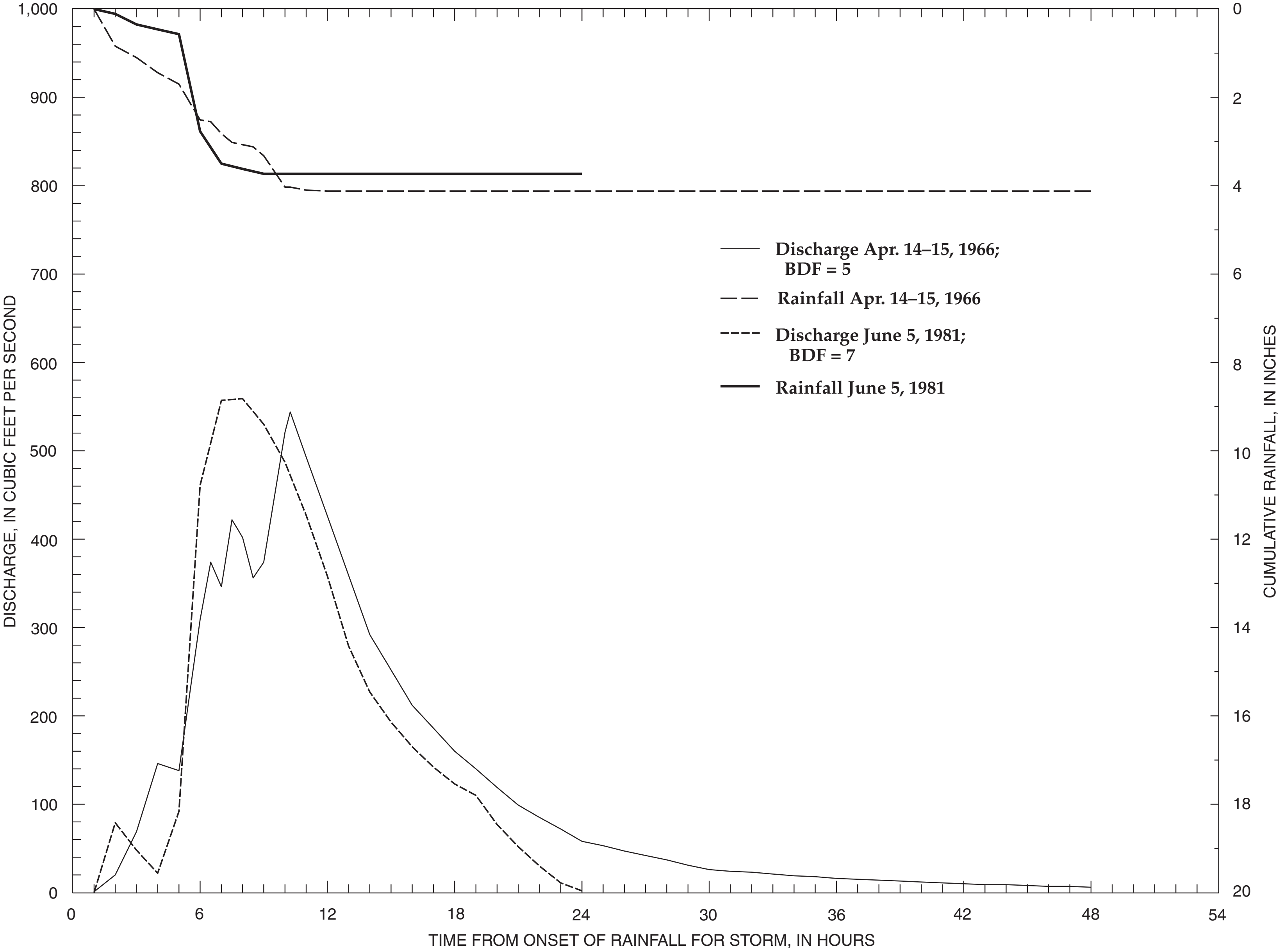

Figure 8c. Hydrograph for 08075550 Berry Bayou at Gilpin St. showing effects of small increase in basin development factor (BDF).

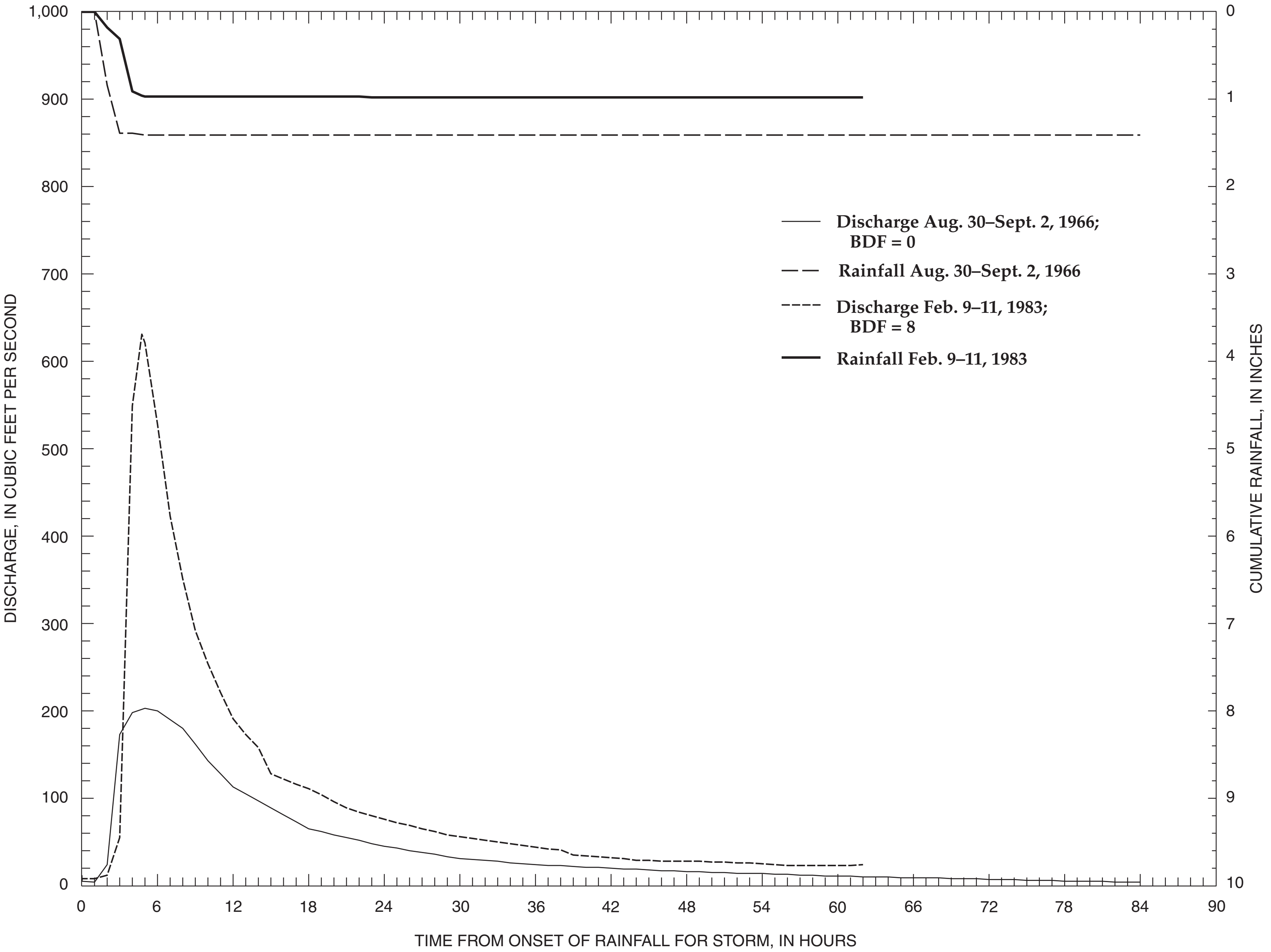

Figure 8d. Hydrograph for 08074800 Keegans Bayou at Roark Rd. showing effects of large increase in basin development factor (BDF).

Table 7. Percent change in stormwater runoff characteristics for selected increases in basin development factor

[TRISE not included because BDF not significant in equation for TRISE; abbreviations of characteristics defined in table 2]

Case	BDF increase in equation	Region	Percent change in stormwater runoff characteristic							
			QPEAK	YPEAK	ROVOL	RODUR	Q75DUR	Q50DUR	TRECES	BLAG
--	0 to 12	1	1,340	1,580	118	-44.1	-82.4	-84.3	-57.9	-86.5
		2	1,456	1,456	98.9	-67.6	-80.9	-83.9	-70.3	-91.7
1	3 to 6	1	44.9	48.0	11.4	-7.78	-21.5	-22.7	-11.3	-24.3
		2	46.5	46.5	10.0	-14.5	-20.6	-22.4	-15.5	-29.2
2	5 to 8	1	63.0	67.7	15.3	-10.1	-27.3	-28.8	-14.6	-30.7
		2	65.4	65.4	13.4	-18.6	-26.2	-28.4	-19.9	-36.6
3	7 to 12	1	545	618	72.1	-33.4	-70.3	-72.6	-45.3	-75.3
		2	580	580	61.6	-54.5	-68.6	-72.0	-57.2	-82.4
4	1 to 9 (largest observed change)	1	213	235	39.5	-22.1	-52.5	-54.8	-30.9	-57.6
5	0 to 8.5 (largest observed change)	2	211	211	32.9	-37.2	-49.6	-53.0	-39.5	-64.2

case, a change from a completely undeveloped basin (BDF = 0) to a completely developed basin (BDF = 12) showed extreme changes for QPEAK, YPEAK, and ROVOL. The equations predict potential changes in QPEAK and YPEAK in regions 1 and 2 of about 1,300 to about 1,600 percent and in ROVOL of about 100 to about 120 percent (table 7). However, changes of this magnitude are unlikely. No basin in the study area showed such a large change in BDF during the study. Five other cases using more representative changes in BDF were used to estimate the effects of increasing urban development in regions 1 and 2. The cases (three hypothetical and two observed) are

1. BDF increases from a low-development value of 3 to a moderate-development value of 6: The case-1 changes in development caused computed QPEAK and YPEAK for both regions to increase about 45 percent and computed ROVOL to increase about 10 percent (table 7).
2. BDF increases from 5 (the 25th percentile [table 2]) to 8 (the 75th percentile): These mid-range increases in development caused computed QPEAK and YPEAK for both regions to increase about 65 percent and computed ROVOL to increase about 15 percent.
3. BDF increases from a moderate-development value of 7 to a completely developed value of 12: In this case, the development increase caused computed QPEAK and YPEAK for region 1 to increase about 545 and 620 percent, respectively; and for region 2 both characteristics increased about 580 percent. Computed ROVOL for regions 1 and 2 increased about 72 and 62 percent, respectively.

From the results of these three hypothetical cases, the characteristics that define the magnitude of stormwater runoff increase at a greater rate as basin development increases.

4. BDF increases from 1 to 9, the largest observed change in region 1 (for station 08075900 [fig. 3]).
5. BDF increases from 0 to 8.5, the largest observed change in region 2 (for station 08074800 [fig. 3]).

The observed increases in development in regions 1 (case 4) and 2 (case 5) during the study increased computed QPEAK about 212 percent, computed YPEAK about 210 to 235 percent, and computed ROVOL about 33 to 40 percent.

Characteristics That Describe Shape and Duration of Storm Hydrograph

RODUR, Q75DUR, Q50DUR, TRECES, and BLAG define storm hydrograph shape and duration. BDF is a significant variable in the equation for estimating each of these characteristics. Increasing urban development causes each of these characteristics to decrease, all other factors being equal. This follows from the fact that the drainage efficiency for the basin increases as the basin is developed.

As with the characteristics that define the magnitude of stormwater runoff, the effects of increases in urban development on RODUR, Q75DUR, Q50DUR, TRECES, and BLAG were estimated from the equations by varying BDF in computations of the characteristics. As with the characteristics that define the magnitude of stormwater runoff, the percent changes in the five shape and duration characteristics depend on the beginning and ending values of BDF as well as on the range of change in BDF. The development scenarios were the same as those for QPEAK, YPEAK, and ROVOL. Not surprisingly, the most extreme case, a change from a completely undeveloped basin (BDF = 0) to a completely developed basin (BDF = 12) resulted in the greatest decreases in the five characteristics (table 7). For this case, decreases in the characteristics ranged from about 44 percent for computed RODUR in region 1 to about 92 percent for computed BLAG in region 2. For the three hypothetical, more representative cases of increased development, the decreases ranged from about 8 percent for computed RODUR in region 1 to about 82 percent for computed BLAG in region 2. As with the characteristics that define the magnitude of stormwater runoff, the rates of change in the shape and duration characteristics increase as basin development increases—but in the opposite direction from the magnitude-defining characteristics. For the largest increases in BDF in regions 1 and 2 observed during the study, decreases in shape and duration characteristics ranged from about 22 percent for computed RODUR in region 1 to about 64 percent for computed BLAG in region 2.

SUMMARY

A study was done by the U.S. Geological Survey, in cooperation with the Harris County Flood Control District and the City of Houston, to estimate the effects of urban development in the Houston, Texas, metropolitan area on nine stormwater runoff characteristics. Three of the nine characteristics define the magnitude of stormwater runoff (peak flow, peak yield, and direct runoff), and the remaining six characteristics describe the shape and duration of a storm hydrograph (direct runoff duration, time of rise to peak flow, duration of flow that equals or exceeds 75 percent of peak flow, duration of flow that equals or exceeds 50 percent of peak flow, time of recession from peak flow to base flow, and basin lag). Multiple linear regression was used to develop equations to estimate the nine stormwater runoff characteristics from basin and rainfall characteristics. Five basin characteristics (drainage area, slope factor, soil index, basin development factor, and percent of urban development) and five rainfall characteristics (total rainfall, maximum 60-minute rainfall, rainfall duration, 85-percent duration [the shortest time in which 85 percent of the rainfall occurred], and antecedent rainfall index) were tested in the regressions to determine which basin and rainfall characteristics significantly affect stormwater runoff characteristics. Basin development factor was found to be significant in equations for eight of the nine stormwater runoff characteristics (all except time of rise to peak flow). Basin development factor is an index of the prevalence of four drainage features—channel improvements, channel linings, storm sewers, and curb-and-gutter streets—and can range from 0 (drainage features not prevalent in a basin) to 12 (drainage features prevalent throughout a basin). Two sets of equations were developed, one for each of two regions based on soil type, from a database containing 1,089 storm discharge hydrographs for 42 sites compiled during 1964–89. Region 1 is an area north of Buffalo Bayou that contains 22 sites, and region 2 is an area south of Buffalo Bayou that contains 20 sites. Soils are more permeable in region 1 than in region 2.

The effects of urban development on the eight stormwater runoff characteristics were quantified by varying basin development factor in the equations and recomputing the stormwater runoff characteristics. Increasing urban development, as represented by increasing basin development factor in the equations, increases the three stormwater runoff characteristics that define the magnitude of stormwater runoff and decreases the five characteristics that describe the shape and duration of a storm hydrograph. Storm hydrographs show that the magnitude of stormwater runoff and the hydrograph shape and duration change only slightly for basins that have undergone small increases in development; however, storm hydrographs show much larger changes in the magnitude of stormwater runoff and the hydrograph shape and duration for basins that have undergone large increases in development.

The largest observed increase in basin development factor for region 1 during the study was from 1 to 9. Corresponding increases in the characteristics that define magnitude of stormwater runoff ranged from about 40 percent (for direct runoff) to 235 percent (for peak yield). Corresponding decreases in the characteristics that describe hydrograph shape and duration ranged from about 22 percent (for direct runoff duration) to about 58 percent (for basin lag). The largest observed increase in basin development factor for region 2 during the study was from 0 to 8.5. Corresponding increases in the characteristics that define magnitude of stormwater runoff ranged from about 33 percent (for direct runoff) to about 210 percent (for both peak flow and peak yield). Corresponding decreases in the characteristics that describe hydrograph shape and duration ranged from about 38 percent (for direct runoff duration) to about 64 percent (for basin lag).

REFERENCES CITED

A.H. Belo, Corp., 1991, 1992–93 Texas almanac and State industrial guide: Dallas, Tex., The Dallas Morning News, Inc., 656 p.

Bedient, P.B., and Huber, W.C., 1988, Urban hydrology, *in* Hydrology and floodplain analysis: Reading, Mass., Addison-Wesley, p. 335–419.

Johnson, S.L., and Sayre, D.M., 1973, Effects of urbanization on floods in the Houston, Texas, metropolitan area: U.S. Geological Survey Water-Resources Investigations Report 3–73, 50 p.

Leopold, L.B., 1968, Hydrology for urban land planning—A guidebook on the hydrologic effects of urban land use: U.S. Geological Survey Circular 554, 18 p.

Linsley, R.K., Kohler, M.A., and Paulhus, J.L.H., 1982, Hydrology for engineers: New York, McGraw-Hill, 508 p.

Liscum, Fred, Brown, D.W., and Kasmarek, M.C., 1996, Summary of surface-water hydrologic data for the Houston metropolitan area, Texas, water years 1964–89: U.S. Geological Survey Open-File Report 96–250, 44 p.

Liscum, Fred, and Massey, B.C., 1980, Technique for estimating the magnitude and frequency of floods in the Houston, Texas, metropolitan area: U.S. Geological Survey Water-Resources Investigations Report 80–17, 29 p.

Ott, R.L., 1993, An introduction to statistical methods and data analysis: Belmont, Calif., Wadsworth Publishing Co., 1,031 p.

P–STAT, Inc., 1989, Regression—Linear relationships, *in* User's manual: Princeton, N.J., ISBN 0–933754–08–06, v. II, p. 42.1–42.27.

Ramos, M.G., ed., 1997, 1998–1999 Texas almanac: Dallas, Tex., The Dallas Morning News, Inc., 672 p.

Sauer, V.B., Thomas, W.O., Jr., Stricker, V.A., and Wilson, K.V., 1983, Flood characteristics of urban watersheds in the United States: U.S. Geological Survey Water-Supply Paper 2207, 63 p.

Southard, R.E., 1986, An alternative basin characteristic for use in estimating impervious area for urban Missouri basins: U.S. Geological Survey Water-Resources Investigations Report 86–4362, 21 p.

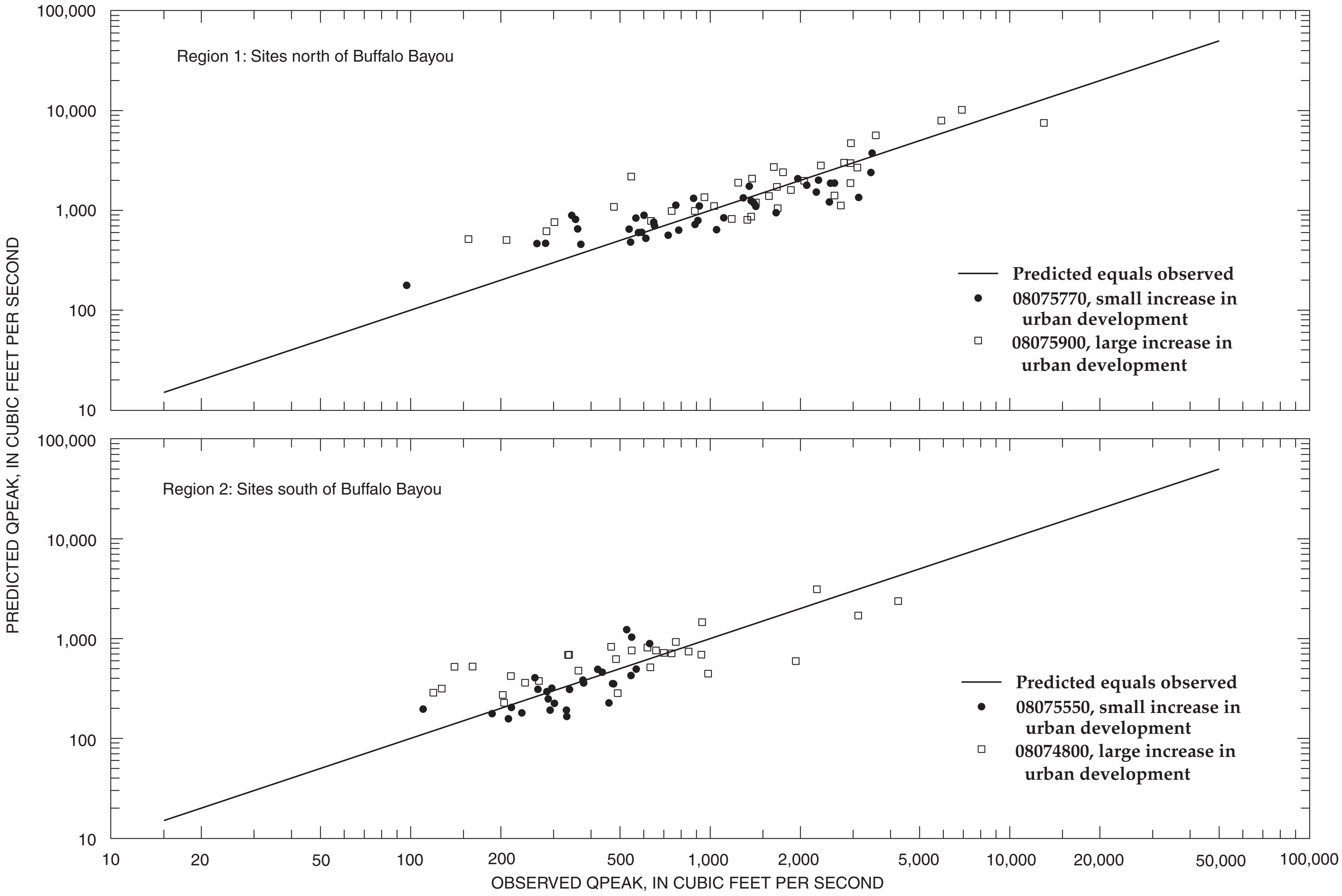

Figure 7a. Observed versus predicted peak flow (QPEAK) for selected streamflow-gaging stations reflecting small and large increases in urban development, by region.

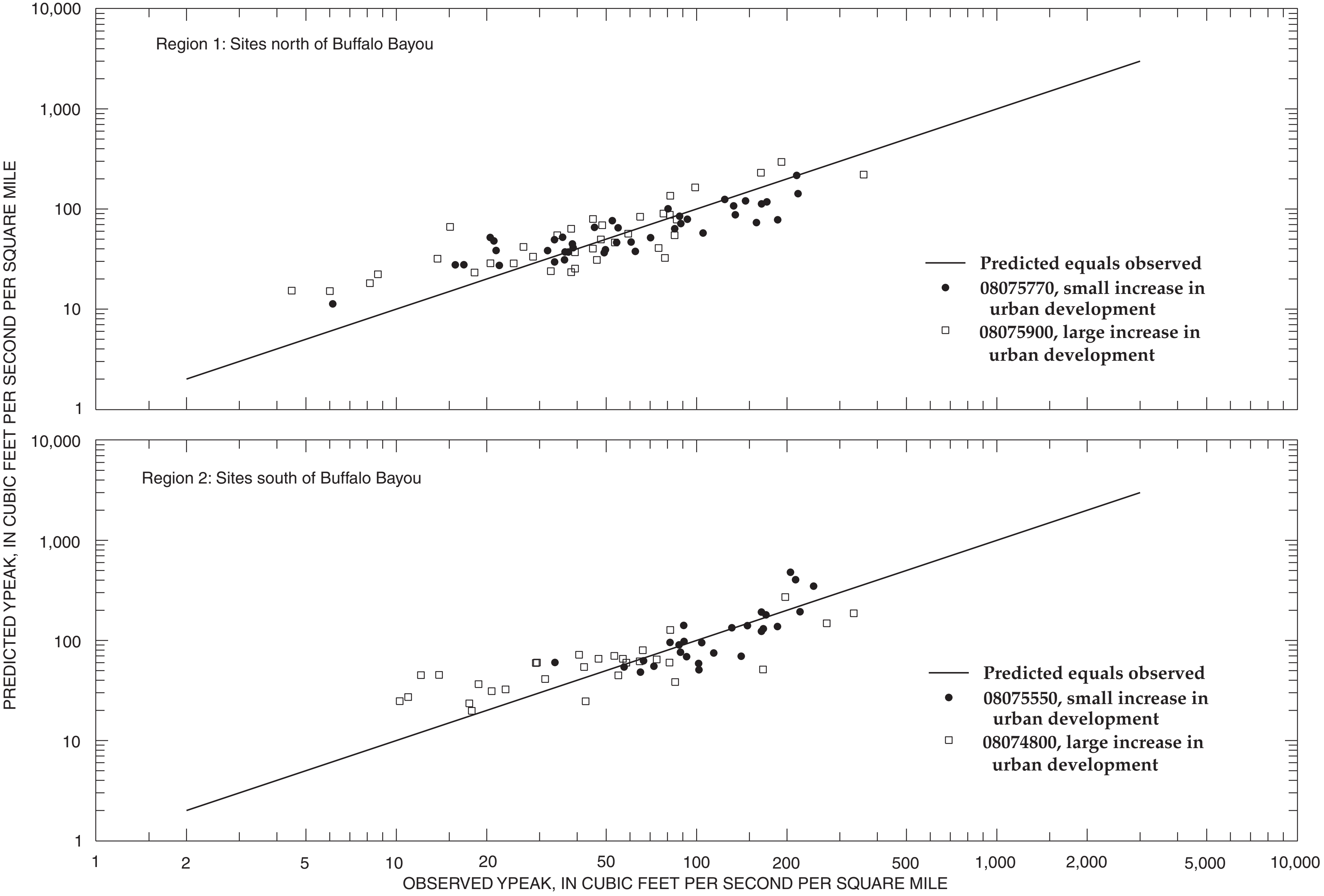

Figure 7b. Observed versus predicted peak yield (YPEAK) for selected streamflow-gaging stations reflecting small and large increases in urban development, by region.

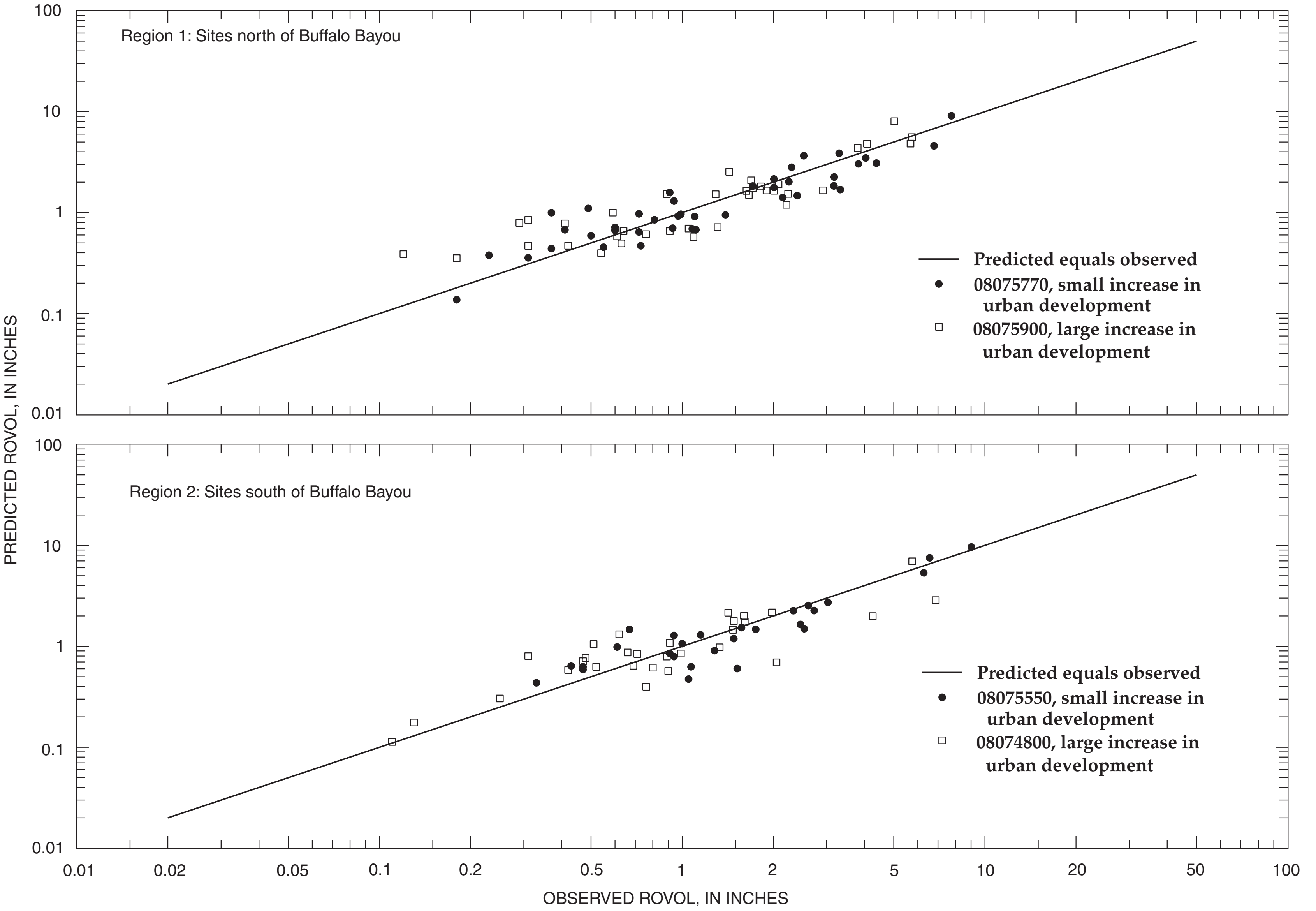

Figure 7c. Observed versus predicted direct runoff (ROVOL) for selected streamflow-gaging stations reflecting small and large increases in urban development, by region.

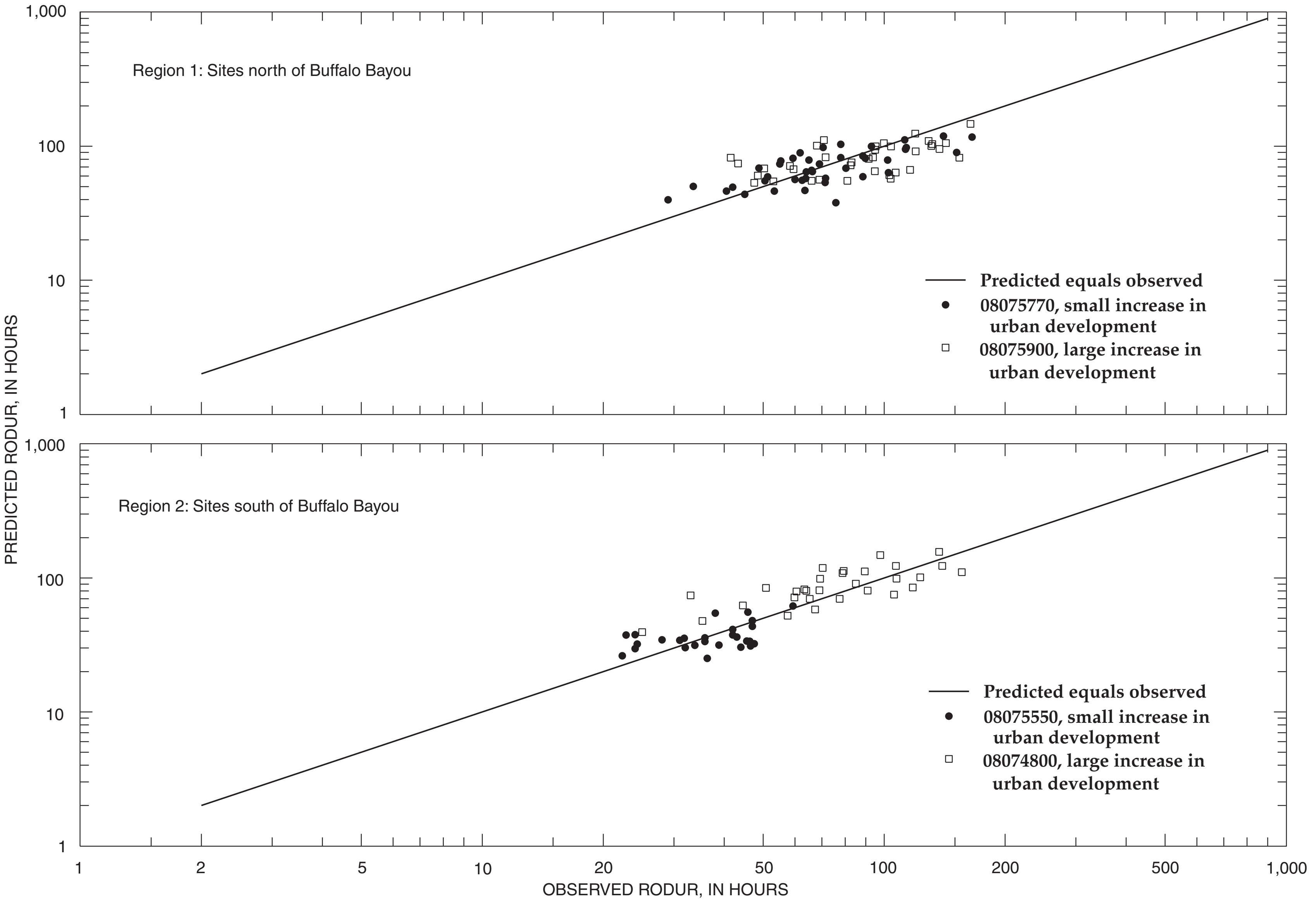

Figure 7d. Observed versus predicted direct runoff duration (RODUR) for selected streamflow-gaging stations reflecting small and large increases in urban development, by region.

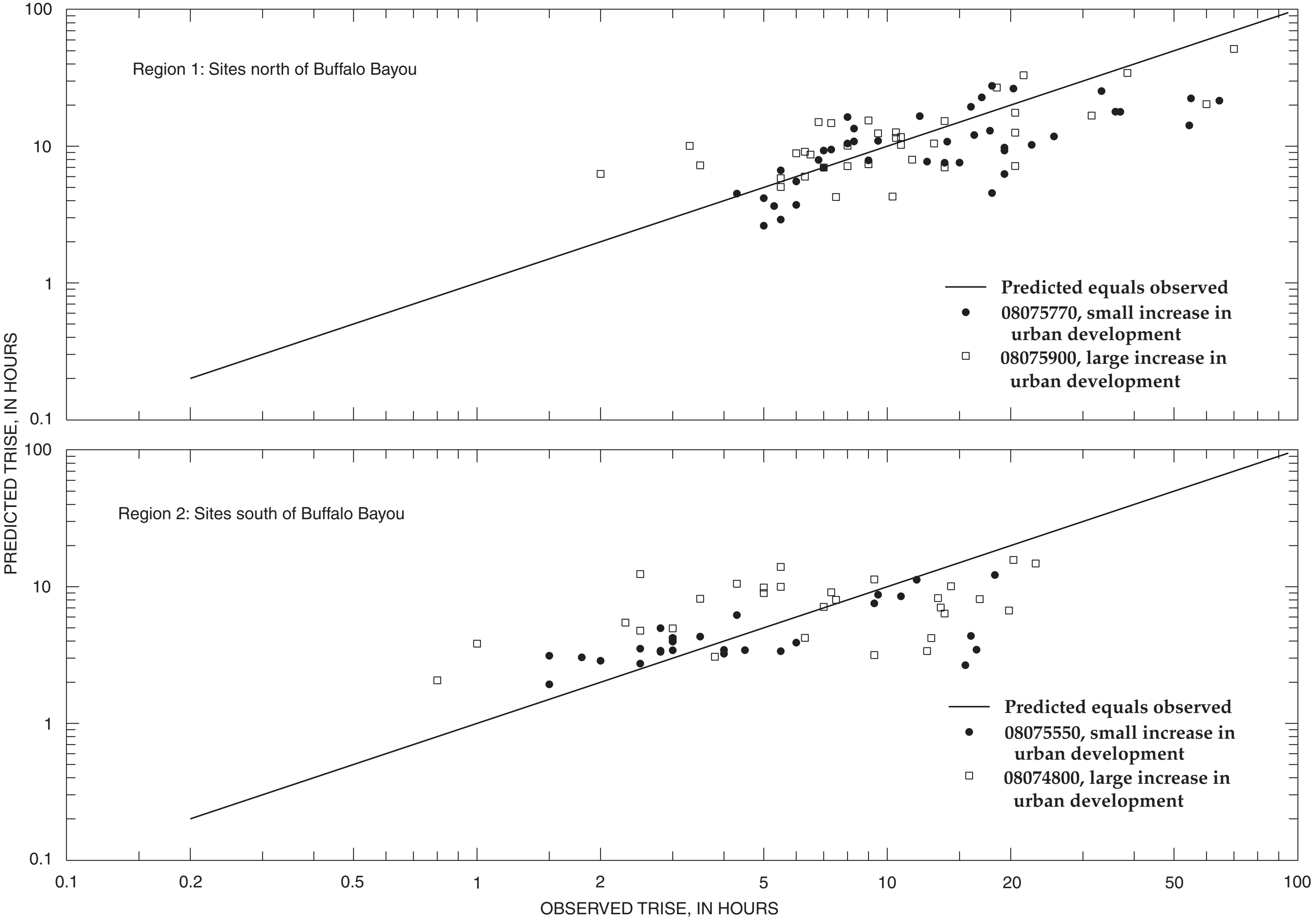

Figure 7e. Observed versus predicted time of rise to peak flow (TRISE) for selected streamflow-gaging stations reflecting small and large increases in urban development, by region.

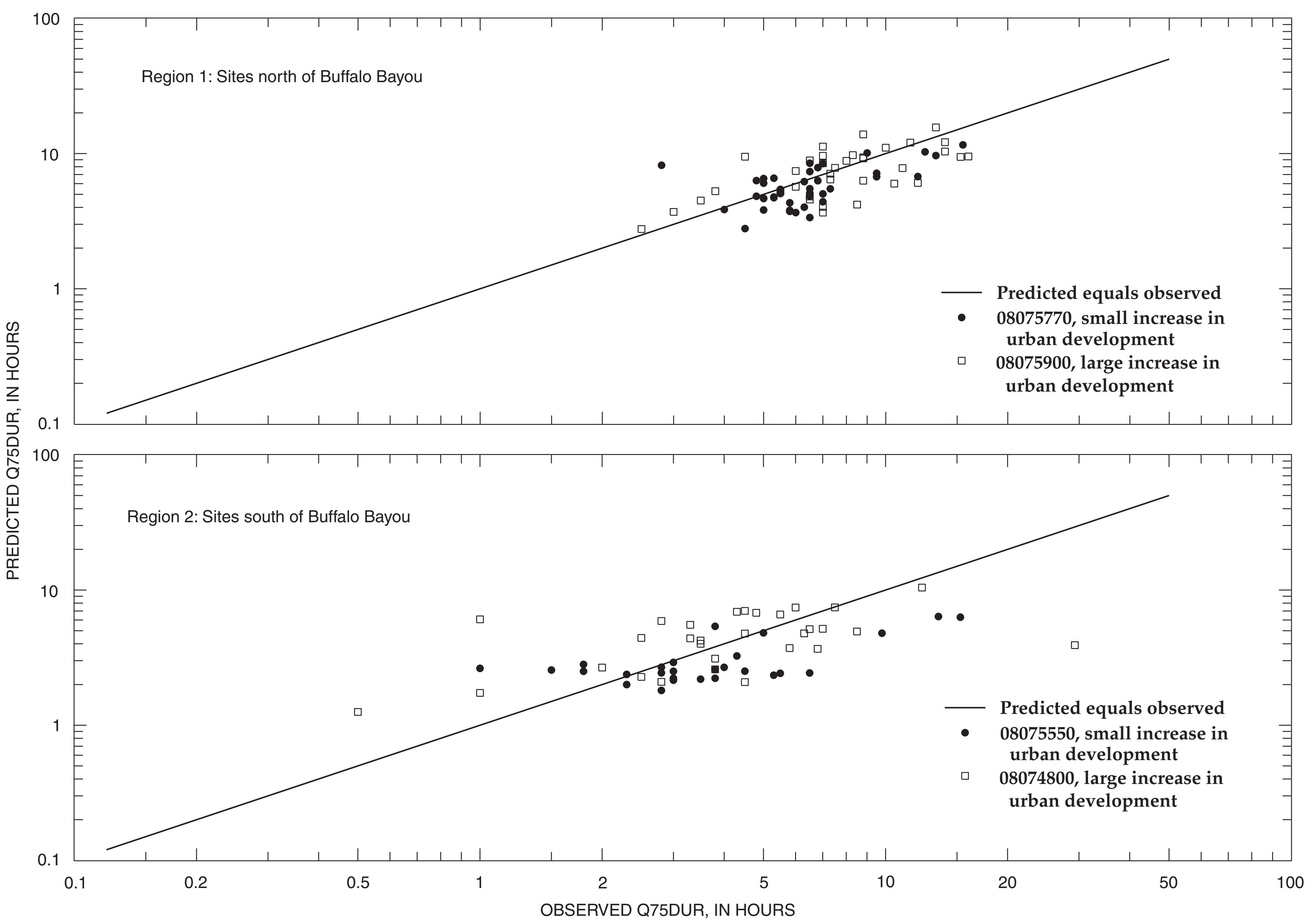

Figure 7f. Observed versus predicted duration of flow that equals or exceeds 75 percent of peak flow (Q75DUR) for selected streamflow-gaging stations reflecting small and large increases in urban development, by region.

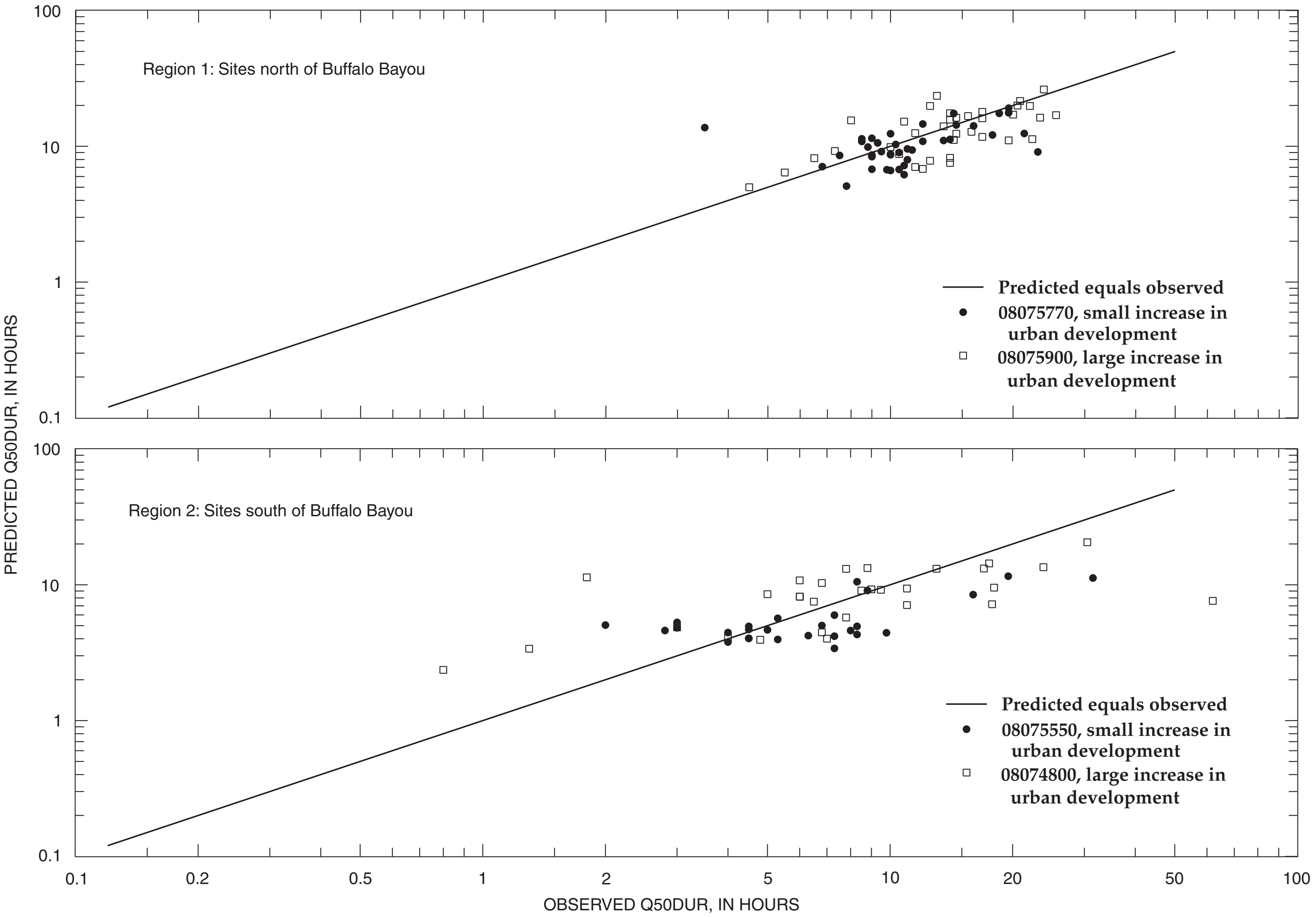

Figure 7g. Observed versus predicted duration of flow that equals or exceeds 50 percent of peak flow (Q50DUR) for selected streamflow-gaging stations reflecting small and large increases in urban development, by region.

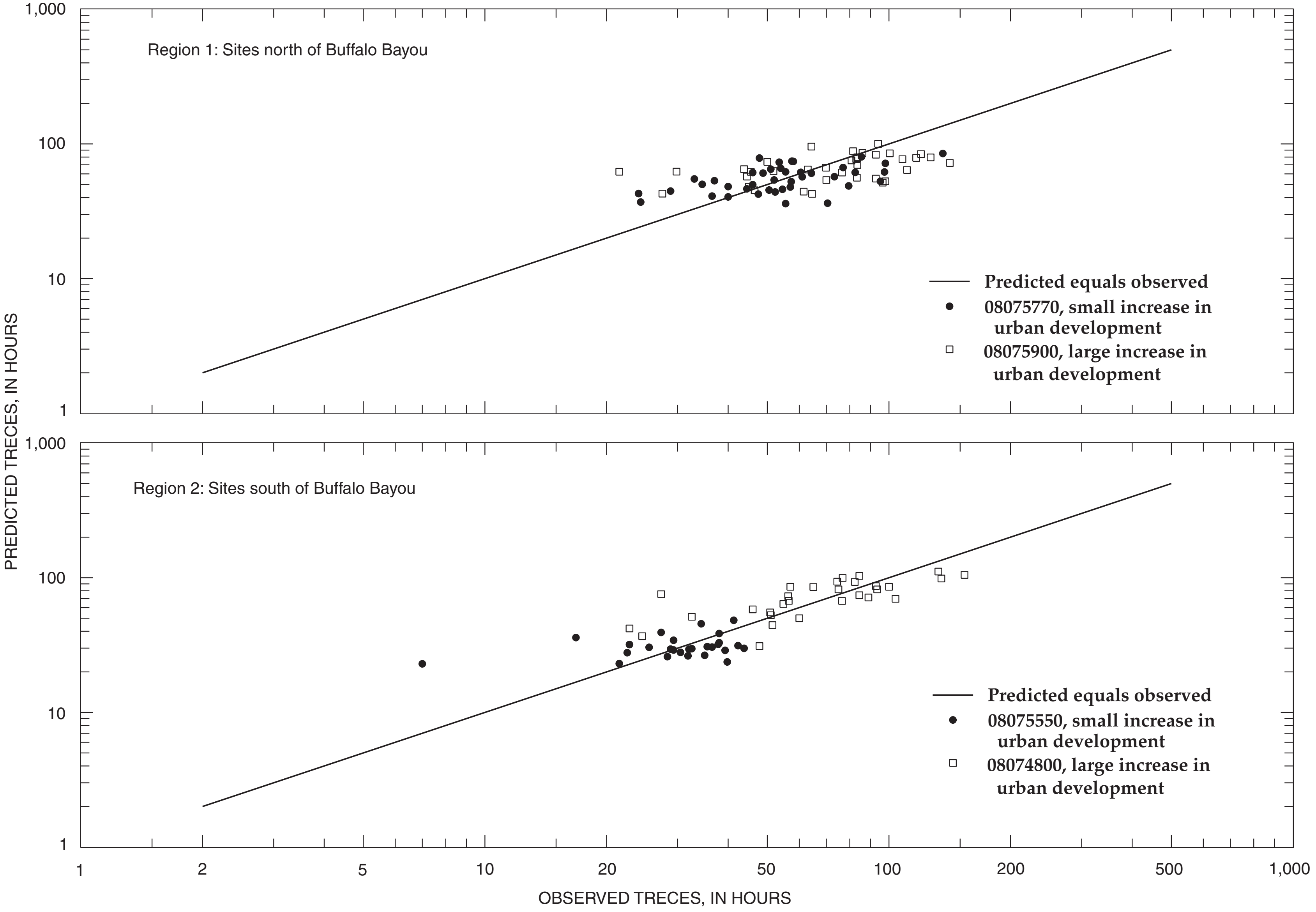

Figure 7h. Observed versus predicted time of recession from peak flow to base flow (TRECES) for selected streamflow-gaging stations reflecting small and large increases in urban development, by region.

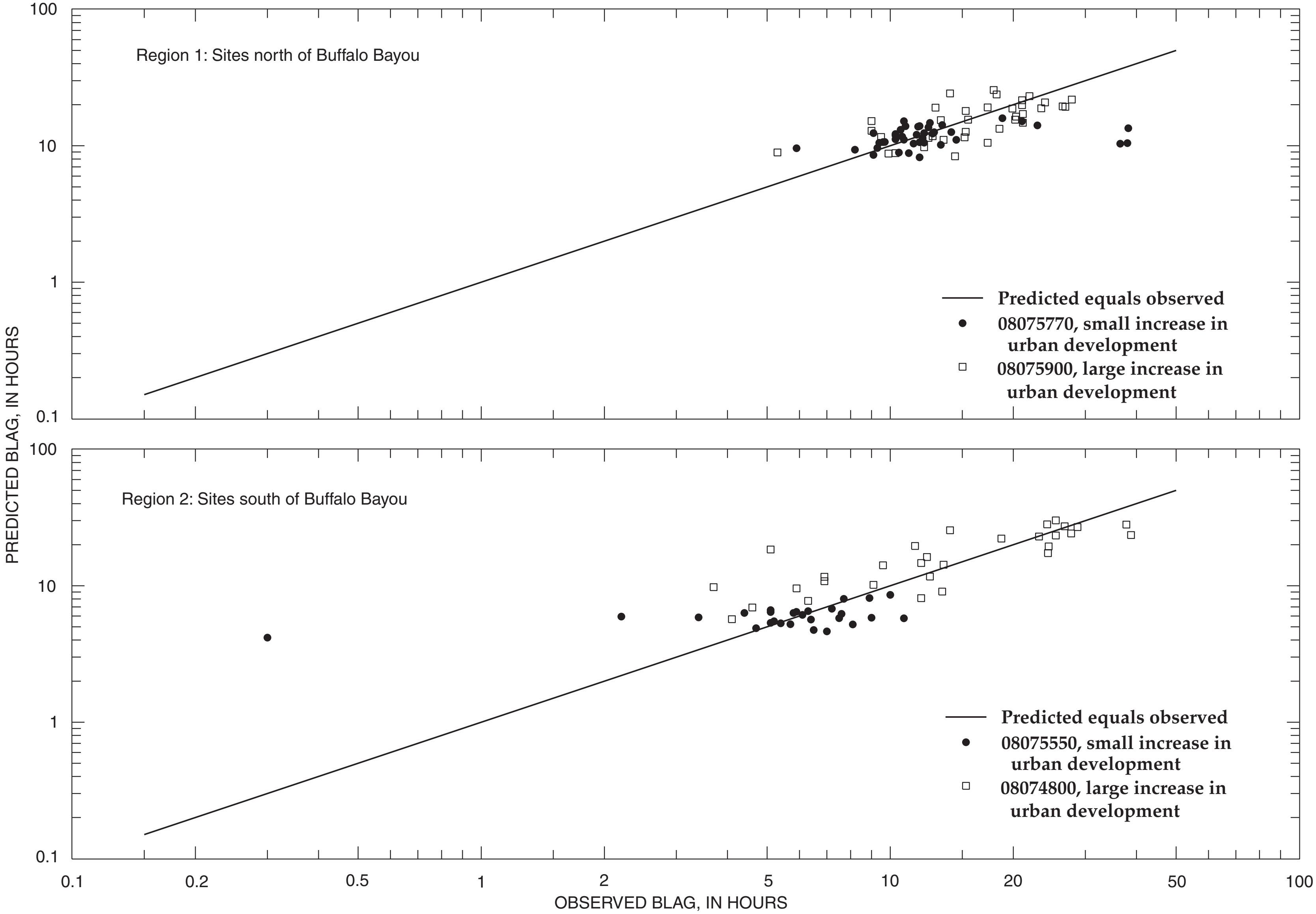

Figure 7i. Observed versus predicted basin lag (BLAG) for selected streamflow-gaging stations reflecting small and large increases in urban development, by region.

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