EXHIBIT B

Use of the Rational Method and Modified Rational Methods for TxDOT Hydraulic Design: Development of Guidance for Runoff Coefficient Selection and Examination of Temporal and Rainfall Depth Sensitivity

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Abstract

The rational and modified-rational method are tools hydraulic engineers use to estimate design discharge for sizing a variety of drainage structures. The method(s) are relatively simple: The peak discharge Q_p is equal to the product of the drainage area A, the rainfall intensity I, and a runoff coefficient c. The last two terms, I and c, are dependent on analyst estimates of time-of-concentration and watershed conditions. Furthermore there is evidence that the runoff coefficient, c, is dependent on rainfall depth, thus the two terms are correlated and the simple model becomes quite non-linear.

This project proposes to evaluate appropriate conditions for use of rational and modified-rational methods for design on small watersheds, evaluate and refine if necessary current tabulated values of the runoff coefficient, and construct guidelines for TxDOT analysts for the selection of appropriate parameter values for Texas conditions.

1 Background and Significance of Work

Texas Department of Transportation (TxDOT) analysts design roadways and proximal infrastructure. Each year, billions of dollars are spent on new construction[1]. The infrastructure must accomodate storm-water drainage and conveyance.

The rational method (Kuichling, 1889) is a tool for estimating peak (maximum) discharge from relatively small drainage areas that predates the age of the automobile. TxDOT guidance is that the rational method should be applied to watersheds with drainage areas of 200 acres or smaller[2].

[1] As described by George "Rudy" Herrmann, TxDOT, on March 10, 2006, approximately 40 percent of construction dollars are spent on drainage-related facilities.

[2] Hydraulic Design Manual, pg. 5–29, TxDOT 3/2004, located electronically at `http://manuals.dot.state.tx.us/dynaweb/colbridg/hyd` at the time of this writing.

The rational method relates peak discharge to contributing drainage area, average rainfall intensity for a duration equal to a watershed response time (typically the time of concentration), and a coefficient that represents hydrologic abstractions and hydrograph attenuation. The coefficient is generally termed the *runoff coefficient* and has a range from 0 (no runoff) to 1 (complete runoff). The modified rational method extends the idea to parameterize simple runoff hydrographs (typically triangular), where the peak of the hydrograph is the peak discharge estimated by application of the rational method, and the time base of the hydrograph (start-to-finish) is twice the time of concentration. Equation 1 is representative of the classical rational equation.

$$Q_p = ciA \tag{1}$$

In equation 1, c is the runoff coefficient (dimensionless if all other terms are in consistent length and time units) that relates the ratio of input volume rate iA to the output volume rate Q_p. The various assumptions of the method are listed in the TxDOT design manual, of particular note is that the runoff coefficient can vary with rainfall intensity i. The rainfall intensity i is, by definition, the rainfall rate when the duration of rainfall equals the time of concentration.

Because the rational method remains in wide usage both within the agency, as well as outside the agency, TxDOT research supervisory personnel issued a problem statement, *Use of the rational and modified rational methods for TxDOT hydraulic design*, in the spring of 2007. The project objectives (from the problem statement) are:

> The project objectives are to evaluate the appropriateness of using both rational and modified rational methods for small watershed design, evaluate the tabulated values of the runoff coefficient, and construct guidelines for TxDOT analysts for selection of appropriate parameter values for Texas watershed conditions.

A number of issues are associated with use of the rational method for estimating peak discharges for design of drainage structures, and when the modified rational method is used to estimate inflow hydrographs for design of best management practices. From the problem statement,

> Use of either method depends on the analysts estimate of the time of concentration and the runoff coefficient. Both of these estimates can vary substantially depending on watershed conditions. Therefore, research to document appropriate values is needed.

In addition to estimates of both time of concentration and runoff coefficient, design-rainfall intensity has an impact. An initial investigation of the rational method, in the context of watershed scale, was reported by Thompson (2007). That work was done using data from about 20 Texas watersheds, mostly rural (undeveloped). The researchers reported (Thompson, 2007)

> For simple watersheds, the rational method may be applied when only an estimate of the peak discharge from the runoff hydrograph is required. Watershed drainage area does not seem to be an important consideration. However, this observation must be tempered with a caveat that only 20 watersheds were examined. Furthermore, watershed complexity was not examined as part of this research. Because the rational method is a simple procedure, application of the method to a complex watershed would be an error

of judgment and may result in substantial errors in estimated design discharge. Further study through expansion of the study database also is in order.

1.1 Database

A database is presented in Asquith et al. (2004), comprising about 100 watersheds ranging in drainage area from about 0.5 square miles to 150 square miles. These stations are listed in table 1.

Table 1: Stations included in paired rainfall and runoff database [adapted from Asquith and Thompson (2005)]
[sub., subwatershed; U, undeveloped watershed; D, developed watershed; —, not applicable]

Number	Station name	Latitude	Longitude	Landuse
08042650	North Creek sub. 28A near Jermyn, Tex.	33°14'52"	98°19'19"	U
08042700	North Creek near Jacksboro, Tex.	33°16'57"	98°17'53"	U
08048520	Sycamore Creek at IH 35W, Fort Worth, Tex.	32°39'55"	97°19'16"	D
08048530	Sycamore Creek tributary above Seminary South Shopping Center, Fort Worth, Tex.	32°41'08"	97°19'44"	D
08048540	Sycamore Creek tributary at IH 35W, Fort Worth, Tex.	32°41'18"	97°19'11"	D
08048550	Dry Branch at Blandin Street, Fort Worth, Tex.	32°47'19"	97°18'22"	D
08048600	Dry Branch at Fain Street, Fort Worth, Tex.	32°46'34"	97°17'18"	D
08048820	Little Fossil Creek at IH 820, Fort Worth, Tex.	32°50'22"	97°19'20"	D
08048850	Little Fossil Creek at Mesquite Street, Fort Worth, Tex.	32°48'33"	97°17'28"	D
08050200	Elm Fork Trinity River sub. 6 near Muenster, Tex.	33°37'13"	97°24'15"	U
08052630	Little Elm Creek sub. 10 near Gunter, Tex.	33°24'33"	96°48'41"	U
08052700	Little Elm Creek near Aubrey, Tex.	33°17'00"	96°53'33"	U
08055580	Joes Creek at Royal Lane, Dallas, Tex.	32°53'43"	96°41'36"	D
08055600	Joes Creek at Dallas, Tex.	32°51'33"	96°53'00"	D
08055700	Bachman Branch at Dallas, Tex.	32°51'37"	96°51'13"	D
08056500	Turtle Creek at Dallas, Tex.	32°48'26"	96°48'08"	D
08057020	Coombs Creek at Sylvan Ave, Dallas, Tex.	32°46'01"	96°50'07"	D
08057050	Cedar Creek at Bonnieview Road, Dallas, Tex.	32°44'50"	96°47'44"	D
08057120	McKamey Creek at Preston Road, Dallas, Tex.	32°57'58"	96°48'11"	U
08057130	Rush Branch at Arapaho Road, Dallas, Tex.	32°57'45"	96°47'44"	D
08057140	Cottonwood Creek at Forest Lane, Dallas, Tex.	32°54'33"	96°45'54"	D

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Table 1: Stations included in paired rainfall and runoff database — Continued

Number	Station name	Latitude	Longitude	Landuse
08057160	Floyd Branch at Forest Lane, Dallas, Tex.	32°54'33"	96°45'34"	D
08057320	Ash Creek at Highland Road, Dallas, Tex.	32°48'18"	96°43'04"	D
08057415	Elam Creek at Seco Boulevard, Dallas, Tex.	32°44'14"	96°41'36"	D
08057418	Fivemile Creek at Kiest Boulevard, Dallas, Tex.	32°42'19"	96°51'32"	D
08057420	Fivemile Creek at US Highway 77W, Dallas, Tex.	32°41'15"	96°49'22"	D
08057425	Woody Branch at IH 625, Dallas, Tex.	32°40'58"	96°49'22"	D
08057435	Newton Creek at IH 635, Dallas, Tex.	32°39'19"	96°44'41"	D
08057440	Whites Branch at IH 625, Dallas, Tex.	32°39'26"	96°44'25"	D
08057445	Prarie Creek at US Highway 175, Dallas, Tex.	32°42'17"	96°40'11"	D
08057500	Honey Creek sub. 11 near McKinney, Tex.	33°18'12"	96°41'22"	U
08058000	Honey Creek sub.12 near McKinney, Tex.	33°18'20"	96°40'12"	U
08061620	Duck Creek at Buckingham Road, Garland, Tex.	32°55'53"	96°39'55"	D
08061920	South Mesquite Creek at SH 352, Mesquite, Tex.	32°46'09"	96°37'18"	D
08061950	South Mesquite Creek at Mercury Road, Mesquite, Tex.	32°43'32"	96°34'12"	D
08063200	Pin Oak Creek near Hubbard, Tex.	31°48'01"	96°43'02"	U
08094000	Green Creek sub. 1 near Dublin, Tex.	32°09'57"	98°20'28"	U
08096800	Cow Bayou sub. 4 near Bruceville, Tex.	31°19'59"	97°16'02"	U
08098300	Little Pond Creek near Burlington, Tex.	31°01'35"	96°59'17"	U
08108200	North Elm Creek near Cameron, Tex.	30°55'52"	97°01'13"	U
08111025	Burton Creek at Villa Maria Road, Bryan, Tex.	30°38'48"	96°20'57"	D
08111050	Hudson Creek near Bryan, Tex.	30°39'38"	96°17'59"	U
08136900	Mukewater Creek sub. 10A near Trickham, Tex.	31°39'01"	99°13'30"	U
08137000	Mukewater Creek sub. 9 near Trickham, Tex.	31°41'40"	99°12'18"	U
08137500	Mukewater Creek at Trickham, Tex.	31°35'24"	99°13'36"	U
08139000	Deep Creek sub. 3 near Placid,Tex.	31°17'25"	99°09'22"	U
08140000	Deep Creek sub. 8 near Mercury, Tex.	31°24'08"	99°07'17"	U
08154700	Bull Creek at Loop 360, Austin, Tex.	30°22'19"	97°47'04"	U
08155200	Barton Creek at SH 71, Oak Hill, Tex.	30°17'46"	97°55'31"	U
08155300	Barton Creek at Loop 360, Austin, Tex.	30°14'40"	97°48'07"	U
08155550	West Bouldin Creek at Riverside Drive, Austin, Tex.	30°15'49"	97°45'17"	D
08156650	Shoal Creek at Steck Avenue, Austin, Tex.	30°21'55"	97°44'11"	D
08156700	Shoal Creek at Northwest Park, Austin, Tex.	30°20'50"	97°44'41"	D

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Table 1: Stations included in paired rainfall and runoff database — Continued

Number	Station name	Latitude	Longitude	Landuse
08156750	Shoal Creek at White Rock Drive, Austin, Tex.	30°20'21"	97°44'50"	D
08156800	Shoal Creek at 12th Street, Austin, Tex.	30°16'35"	97°45'00"	D
08157000	Waller Creek at 38th Street, Austin, Tex.	30°17'49"	97°43'36"	D
08157500	Waller Creek at 23rd Street, Austin, Tex.	30°17'08"	97°44'01"	D
08158050	Boggy Creek at US 183, Austin, Tex.	30°15'47"	97°40'20"	D
08158100	Walnut Creek at FM 1325, Austin, Tex.	30°24'35"	97°42'41"	U
08158200	Walnut Creek at Dessau Road, Austin, Tex.	30°22'30"	97°39'37"	U
08158380	Little Walnut Creek at Georgian Drive Austin, Tex.	30°21'15"	97°41'52"	D
08158400	Little Walnut Creek at IH 35, Austin, Tex.	30°20'57"	97°41'34"	D
08158500	Little Walnut Creek at Manor Road, Austin, Tex.	30°18'34"	97°40'04"	D
08158600	Walnut Creek at Webberville Road, Austin, Tex.	30°16'59"	97°39'17"	D
08158700	Onion Creek near Driftwood, Tex.	30°04'59"	98°00'29"	U
08158800	Onion Creek at Buda, Tex.	30°05'09"	97°50'52"	U
08158810	Bear Creek below FM 1826, Driftwood, Tex.	30°09'19"	97°56'23"	U
08158820	Bear Creek at FM 1626, Manchaca, Tex.	30°08'25"	97°50'50"	U
08158825	Little Bear Creek at FM 1626, Manchaca, Tex.	30°07'31"	97°51'43"	U
08158840	Slaughter Creek at FM 1826, Austin, Tex.	30°12'32"	97°54'11"	U
08158860	Slaughter Creek at FM 2304, Austin, Tex.	30°09'43"	97°49'55"	U
08158880	Boggy Creek (south) at Circle S Road, Austin, Tex.	30°10'50"	97°46'55"	U
08158920	Williamson Creek at Oak Hill, Tex.	30°14'06"	97°51'36"	D
08158930	Williamson Creek at Manchaca Road, Austin, Tex.	30°13'16"	97°47'36"	D
08158970	Williamson Creek at Jimmy Clay Road, Austin, Tex.	30°11'21"	97°43'56"	D
08159150	Wilbarger Creek near Pflugerville, Tex.	30°27'16"	97°36'02"	U
08177600	Olmos Creek tributary at FM 1535, Shavano Park, Tex.	29°34'35"	98°32'45"	D
08177700	Olmos Creek at Dresden Drive, San Antonio, Tex.	29°29'56"	98°30'36"	D
08178300	Alazan Creek at St. Cloud Street, San Antonio, Tex.	29°27'29"	98°32'59"	D
08178555	Harlendale Creek at West Harding Street, San Antonio, Tex.	29°21'05"	98°29'32"	D
08178600	Panther Springs Creek at FM 2696 near San Antonio, Tex.	29°37'31"	98°31'06"	U
08178620	Lorence Creek at Thousand Oaks Boulevard, San Antonio, Tex.	29°35'24"	98°27'47"	D
08178640	West Elm Creek at San Antonio, Tex.	29°37'23"	98°26'29"	U

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Table 1: Stations included in paired rainfall and runoff database — Continued

Number	Station name	Latitude	Longitude	Landuse
08178645	East Elm Creek at San Antonio, Tex.	29°37'04"	98°25'41"	U
08178690	Salado Creek tributary at Bitters Road, San Antonio, Tex.	29°31'36"	98°26'25"	D
08178736	Salado Creek tributary at Bee Street, San Antonio, Tex.	29°26'38"	98°27'13"	D
08181000	Leon Creek tributary at FM 1604, San Antonio, Tex.	29°35'14"	98°37'40"	U
08181400	Helotes Creek at Helotes, Tex.	29°34'42"	98°41'29"	U
08181450	Leon Creek tributary at Kelly Air Force Base, Tex.	29°23'12"	98°36'00"	D
08182400	Calaveras Creek sub. 6 near Elmendorf, Tex.	29°22'49"	98°17'33"	U
08187000	Escondido Creek sub. 1 near Kenedy, Tex.	28°46'41"	97°53'41"	U
08187900	Escondido Creek sub. 11 near Kenedy, Tex.	28°51'39"	97°50'39"	U
SSSC	Seminary South Shopping Center drainage, Fort Worth, Tex.	—	—	D

Since publication of Asquith et al. (2004), additional watersheds were added to the database to bring the total number of watersheds available for analysis to about 130. Table reftbl:cleveland lists these additional stations and some relevant properties[3]. Figure 1 is a map locating the stations in tables 1, 2, and 3; figure 1 presents the current spatial coverage status of the collective database(s) in use by the research team.

Table 2: Locations, Selected Physical Characteristics, and Unit Hydrograph Values for Study Watersheds in Houston, Texas. adapted from (Cleveland and others 2007)

[TDA, Total drainage area in km^2; MCL, Main channel length in km; SLOPE, Dimensionless main channel slope; DEVF, Basin development factor (0=undeveloped, 1=developed); Q_p, Peak rate factor in $\frac{m^3/s-hr}{mm-km^2}$; T_p, Time to peak in hours]

Station No.	Latitude	Longitude	TDA	MCL	SLOPE	DEVF	Qp	Tp
8068438	30°08'38"	95°28'09"	1.4	1.2	0.0077	0	0.341	0.41
8068440	30°08'24"	95°28'33"	1.8	2.1	0.0062	0	0.133	1.10
8077100	29°36'09"	95°16'41"	3.4	3.0	0.0015	0	0.051	3.27
8075780	29°56'56"	95°31'10"	20.9	6.9	0.0015	0	0.022	6.66
8074780	29°39'55"	95°35'42"	22.4	9.4	0.0019	0	0.046	5.76
8068400	30°11'34"	95°29'09"	67.7	14.3	0.0024	0	0.020	8.81
8068450	30°08'04"	95°28'38"	89.4	22.9	0.0018	0	0.017	10.77
8073630	29°46'32"	95°32'23"	3.6	1.2	0.0041	1	0.086	2.31
8074145	29°51'31"	95°29'09"	0.5	1.1	0.0011	1	0.182	2.77

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[3]Table 2 is in SI Units, converted from U.S. Customary for ASCE publication

Table 2: Locations, Selected Physical Characteristics, and Unit Hydrograph Values for Study Watersheds in Houston, Texas. — Continued

Station No.	Latitude	Longitude	TDA	MCL	SLOPE	DEVF	Qp	Tp
8075300	29°37'33"	95°29'56"	9.9	5.1	0.0028	1	0.046	3.95
8075600	29°39'00"	95°14'18"	4.1	3.6	0.0017	1	0.027	4.57
8075750	29°48'00"	95°20'02"	3.1	2.9	0.0013	1	0.052	2.42
8178555	29°21'05"	98°29'32"	4.9	6.5	0.0024	1	0.093	2.69
8075550	29°38'32"	95°13'22"	6.6	5.4	0.0018	1	0.056	2.23
8074910	29°39'44"	95°29'11"	0.8	2.3	0.0008	1	0.115	1.26
8074100	29°51'24"	95°30'55"	18.3	8.1	0.0023	1	0.030	6.42
8075760	29°48'22"	95°19'50"	6.7	6.5	0.0016	1	0.041	5.40
8075700	29°21'05"	95°15'11"	12.6	6.8	0.0016	1	0.046	3.23
8075650	29°40'35"	95°14'37"	27.7	7.9	0.0016	1	0.023	6.69
8074750	29°43'11"	95°39'37"	2.3	2.8	0.0005	1	0.026	2.46
8075400	29°37'07"	95°26'45"	52.4	10.6	0.0017	1	0.029	8.74
8074150	29°51'04"	95°29'16"	19.4	10.7	0.0013	1	0.024	6.10
8074540	29°47'33"	95°22'06"	46.7	14.5	0.0016	1	0.038	7.68
8075730	29°41'40"	95°12'58"	21.4	8.4	0.0009	1	0.033	6.15
8075770	29°47'35"	95°16'04"	41.7	12.5	0.0012	1	0.044	3.80
8076200	29°54'07"	95°25'21"	23.3	12.4	0.0010	1	0.016	11.09
8074900	29°39'01"	95°29'11"	29.0	12.2	0.0009	1	0.012	13.00
8074760	29°42'39"	95°35'13"	36.5	13.8	0.0008	1	0.019	6.91
8074850	29°41'16"	95°30'20"	11.4	10.9	0.0005	1	0.021	7.44
8076500	29°51'42"	95°20'05"	74.4	24.0	0.0010	1	0.010	14.46
8074500	29°46'30"	95°23'49"	223.7	33.1	0.0011	1	0.022	14.79
8075500	29°40'27"	95°17'21"	163.3	30.3	0.0010	1	0.010	11.52
8074810	29°40'21"	95°31'41"	137.9	22.6	0.0007	1	0.016	12.44
8075000	29°41'49"	95°24'43"	246.0	33.8	0.0007	1	0.008	15.50

1.2 Runoff Coefficient

The runoff coefficient for application of the rational method (and the modified rational method) is generally taken from tables of values published in any standard hydrology text[4]. While the genesis of those standard tables remains unknown, the accepted method for estimating the runoff coefficient is to take the ratio of total runoff to total storm depth,

$$C_v = \frac{\int Q(t)dt}{A \int P(t)dt)}, \quad (2)$$

where C_v is the volumetric runoff coefficient, Q is the instantaneous runoff rate (discharge),A is the watershed area, and P is the instantaneous rainfall rate.

Thompson (2007) used the watersheds listed in table 3 to estimate values of the runoff coefficient from measurements of rainfall and runoff. These watersheds constitute a subset of those presented

[4]See, for example, Viessman and Lewis (2003). Also, a table of runoff coefficients is published in the TxDOT on-line Hydraulic Design Guidelines, located electronically at `http://manuals.dot.state.tx.us/dynaweb/colbridg/hyd` at the time of this writing.

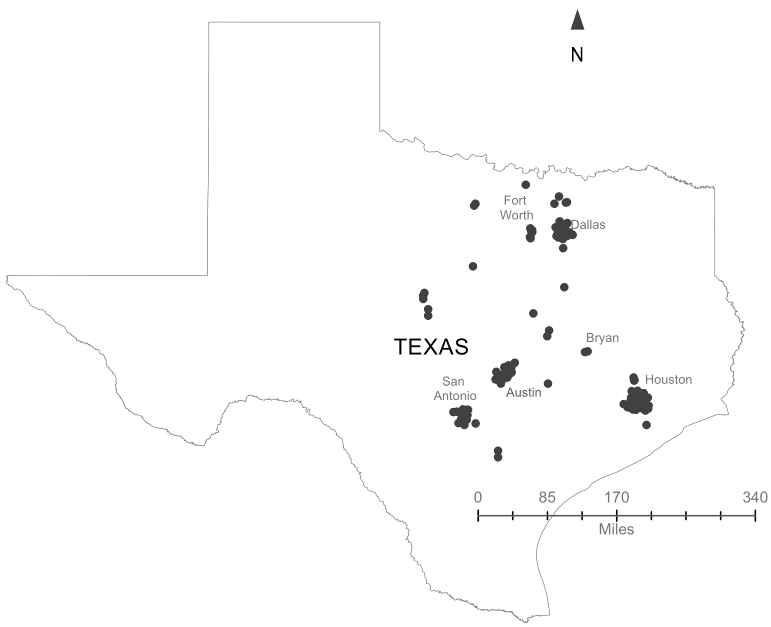

Figure 1: Station locations of stations with paired rainfall-runoff data

in table 1 above. The method used to estimate observed runoff coefficients[5] was that presented by Schaake et al. (1967). Estimates of both observed and predicted (table) runoff coefficient are also presented on table 3.

However, the rational method produces an estimate of the discharge, a rate, using an estimate of the rainfall rate. Therefore, it can be argued that the runoff coefficient should be based on some relation between the rate of runoff (discharge) and the rate of rainfall. That is,

$$C = \frac{Q_p}{i}, \tag{3}$$

where Q_p is the target runoff rate (the peak) and i is some measure of rainfall intensity.

The importance of these two views of how to determine the runoff coefficient is briefly illustrated in the next two sections, where the sensitivity to the time base is examined and evidence of dependence on storm depth is presented.

1.3 Sensitivity to Time of Concentration

The rainfall intensity is sensitive to changes in the time base. To illustrate consider the 2%-chance depths (50-year frequency) for Harris County as shown in table 4. The values in the time column and

[5]Two estimates of runoff coefficient were produced. One was termed the *observed* runoff coefficient because it was extracted from site-specific contemporaneous measurements of rainfall and runoff. The second was termed the *predicted* runoff coefficient because it was taken from tabular estimates.

Table 3: Watersheds, watershed characteristics, and estimates of observed and predicted (table) runoff coefficients from Thompson (2007).

USGS Gage Station ID	USGS Quadrangle Location	Drainage Area (mi^2)	Channel Length (ft)	Channel Slope (ft/ft)	Observed C	Table C
08088100	True	11.8	24,874	0.003	0.45	0.40
08093400	Abbot	12.4	52,689	0.004	0.44	0.37
08160800	Frelsburg	17.3	42,407	0.005	0.27	0.41
08167600	Fischer	10.9	29,393	0.017	0.26	0.68
08156800	Austin	12.3	55,144	0.008	0.70	0.68
08158700	Austin	124	175,221	0.004	0.30	0.40
08158840	Austin	8.24	25,690	0.010	0.40	0.46
08178640	San Antonio	2.45	15,786	0.020	0.35	0.46
08181400	San Antonio	15.0	51,257	0.011	0.38	0.48
08098300	Cameron	23.0	72,642	0.003	0.67	0.38
08096800	Moody	5.47	34,715	0.006	0.34	0.36
08137000	Bangs	4.02	22,238	0.004	0.35	0.36
08182400	Martinez	7.01	25,586	0.006	0.28	0.34
08187000	Lenz	3.29	14,477	0.010	0.16	0.38
08187900	Lenz	8.43	25,011	0.005	0.41	0.39
08050200	Muenster	0.77	13,497	0.011	0.58	0.41
08058000	Weston	1.26	10,283	0.009	0.65	0.36
08052700	Marilee	75.5	122,054	0.002	0.54	0.41
08042700	Senate	21.6	60,538	0.006	0.32	0.44
08063200	Coolidge	17.6	45,847	0.004	0.53	0.36

depth column are estimates from the Texas depth-duration-frequency atlas (Asquith and Roussel, 2004), the intensity is calculated as the ratio of the mapped depth and associated duration [6].

Table 4: Example Rainfall Intensities

Time (min)	Depth (inches)	Intensity (in/min)
15	1.9	0.126
30	2.6	0.086
60	3.8	0.063

Figure 2 is a plot of the relation between rainfall intensity and rainfall duration (storm duration) using values listed in table 4. The curve on the plot is a hyperbolic interpolating function used to illustrate the sensitivity of rainfall intensity to small changes in the time base.

For the curve presented in figure 2, a ten-percent change in time at a duration of 30 minutes causes about a five-percent change in indicated rainfall intensity. That is $i_{30} = 0.084$ while $i_{33} = 0.079$ for values on the curve. At smaller values of time, hence for small watersheds, the change in time greatly impacts the estimated intensity (notice the magnitude of the slope increases at smaller time). At larger values, the effect is reduced — however, if the time of concentration values are large (exceeding, say, about 300 minutes), then either the watershed under consideration is too

[6] Table 4 is constructed from the maps in Asquith and Roussel (2004); not from the provided L-moments

large for application of the rational method or the watershed of interest is in a low-slope region and other methods should be considered[7].

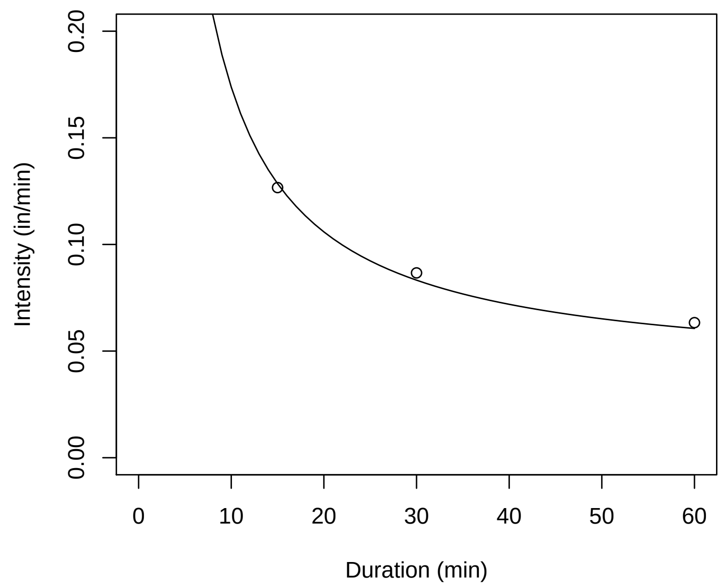

Figure 2: Intensity-duration relationship for 2%-chance storm, Harris County, TX. Markers are values estimated from Asquith and Roussel (2004); curve is a hyperbolic interpolating function passed through the markers

The true nature of sensitivity to time depends on the shape of the curve and the slope (first derivative) of the curve near the time of interest. Small variations at large time are probably irrelevant, small variations at small time will have considerable impact on intensity. Time estimates by several different methods as examined in TxDOT project 0-4696 vary about one-half log cycle of each other so the effect of the time estimate methodology alone is expected to exert considerable influence on rational method peak discharge values on smaller watersheds.

1.4 Storm Depth Dependence

The runoff coefficient is known to be dependent on storm depth as well as watershed properties, and indeed this dependence is implicitly acknowledged in the TxDOT design manual in the coefficient adjustment factors for the rational method. Further illustration of the dependence is offered in the following discussion.

[7] One proposal author suggests that dimensionless slopes in the range 0.002 to 0.0002 define the boundary where kinematic-wave theory begins to fail for hydrologic modeling

Figure 3, upper panel, is a plot of the relationship of runoff depth to storm depth for for about 2600 storms in Texas on 130 different watersheds. The data for the plot were derived from data reported in Asquith and others 2004 [8] supplemented by Houston area watersheds(LiscumOFR)[9]. These data were analyzed in support of TxDOT projects 0–4193, 0–4194, 0–4405, and 0–4696. The line on the plot is an equal value line that illustrates, except for a few percent of the storm pairs, that storms produced runoff depths less than the storm depth — an anticipated response. Also in the upper panel, any reasonable trend line plotted through the marker cloud would have a slope different from, and probably steeper than the equal value line suggesting that the conversion of rainfall depth to runoff depth is dependent on the rainfall depth in a non-linear fashion (the slope of a trend line is conceptually a runoff coefficient).

The lower panel of figure 3 is a plot of the relation of a volumetric runoff coefficient, (Essentially C_v) and storm depth, D_{storm}. The horizontal line is equivalent to the equal value line $D_{runoff} = D_{storm}$. The other line is a power-law trend line fit through the marker cloud by an ordinary least-squares approach. The slope of the line is positive, and more importantly, statistically different from zero, thus providing some evidence of a relationship between the volumetric runoff coefficient and the storm depth.

Figure 4 is a similar set of figures from the same underlying data. Figure 4 differs from figure 3 in that the peak rainfall values and peak discharge values for a one minute interval from the 2,600 storms were extracted and selected for plotting. An implicit assumption in figure 4 is that the peak rainfall causes the peak discharge — similar in concept to the rational method. The lines on each plot are power-law fits ($y = ax^b$) through the marker clouds — in these cases the explanatory variable is the peak one-minute rainfall intensity.

In contrast to the volumetric based runoff coefficients these plots exhibit the opposite behavior, but the meaning is the same; like depth-ratio based coefficients, the runoff coefficient computed by rate ratios appears to be intensity dependent.

The rational method, by its very simplicity, makes it attractive for use in many applications. Care is recommended in the TxDOT manual, however guidance is needed for how to consistently handle issues of temporal sensitivity, intensity dependence, and what are reasonable values of the runoff coefficient for Texas watersheds.

1.5 History

TxDOT uses a handful of methods for estimating discharges for hydraulic designs. Among those methods are the rational method (and modified rational method), the unit hydrograph method, regional regression equations, and streamgage analysis. Although the Hydraulic Design Guidelines offer guidance on method selection, the final choice is left to the analyst.

Over the last ten years, TxDOT funded research focused on improving understanding of their suite of methods for estimating design discharges. In addition, it was the intent of the research to

[8] Watersheds in table 1

[9] Watersheds in table 2

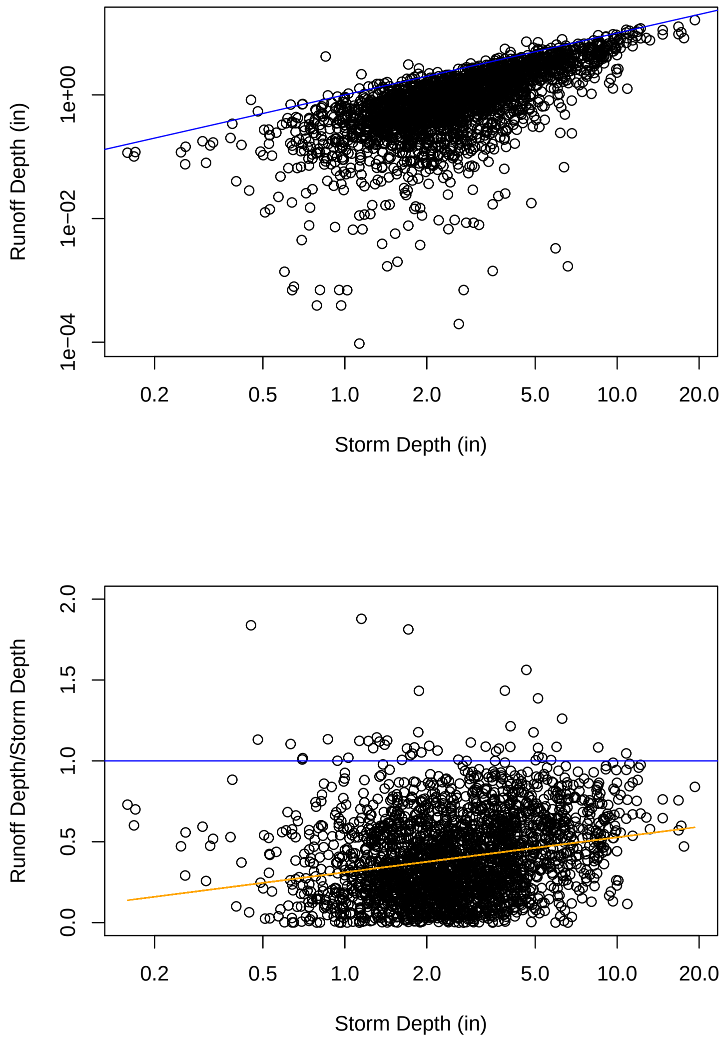

Figure 3: Relationship of $C_v = (\int Q(t)dt / \int P(t)dt)$ to $\int P(t)dt$ for 2600 Texas storms

develop their suite of methods such that increased confidence in design discharge estimates would result. One benefit of improved estimates is reduced reliance on simple conservatism[10]. Much of the research undertaken by this research team focused on a dataset assembled from USGS records encompassing about 100 watersheds and about 1,600 storm events. This dataset includes watersheds from central and eastern Texas and was recently supplemented with additional watersheds and storm events for the Houston area.

[10]One definition of conservatism is the artificial inflating of method parameters to increase discharge estimates with the hope that such practices reduces the risk of hydraulic failure without regard to the impact on project cost.

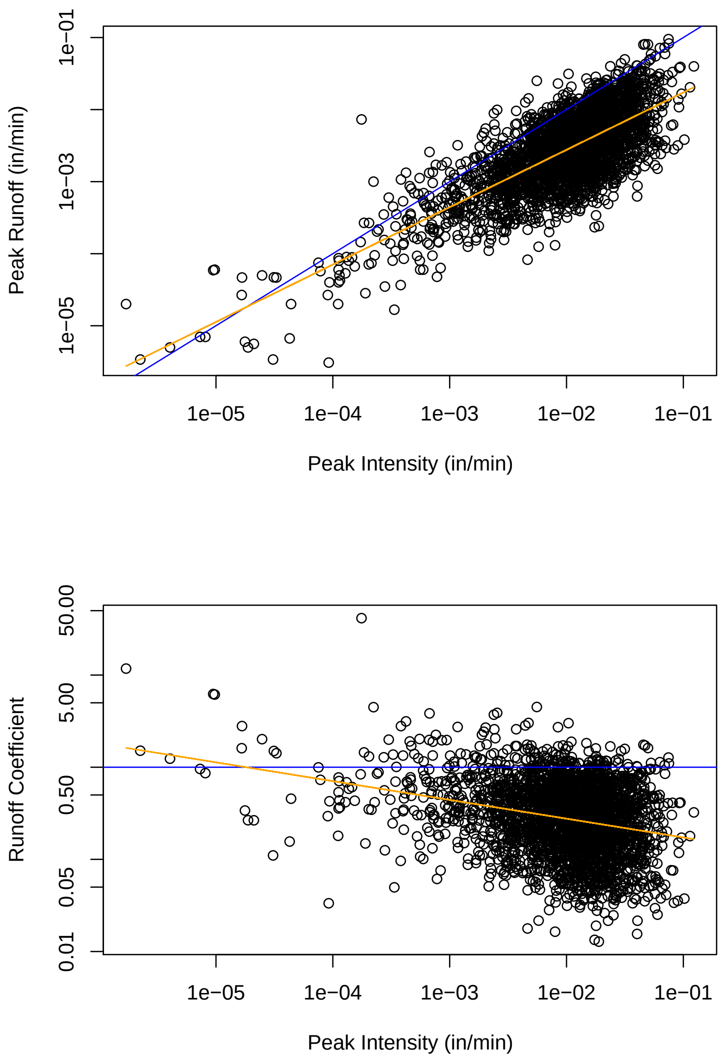

Figure 4: Relationship of Q_p to I (upper panel), and $c = Q_p/I$ (lower panel) for 2600 Texas storms

Recently, an exploratory research project was completed (Thompson, 2007) that examined the relation between hydrologic scale[11] and appropriate method for estimating design discharge. While work on hydrologic scale remains to be done, the work of Thompson (2007) resulted an alternative approach to the Asquith and Slade (1997) regression equations (Asquith and Thompson, 2005) which became another research project (TxDOT Project 0–5521). In addition, Thompson (2007)

[11]Hydrologic scale is often measured in terms of watershed drainage area. One of the conclusions of Thompson (2007) is that drainage area may not be the best parameter for assessing hydrologic scale. More work is needed on this topic.

suggested that drainage area alone may not be a good discriminator for choosing a hydrologic method for estimating a design discharge.

Another result of Thompson (2007) dealt with the rational method and estimates of the runoff coefficient. Two conclusions from Thompson (2007) are pertinent:

1. Estimates of n-year discharge using the rational method are based on best estimates for the runoff coefficient taken from a comparison of measured rainfall and runoff events. Selection of proper estimates of the runoff coefficient is critical for correct estimation of n-year discharges. Refinement of this process beyond simple selection of values from a table is appropriate.

   This observation does not constitute a recommendation for a probabilistic adjustment of runoff coefficient (as recommended in current hydraulic design guidelines). Rather, the observation that runoff coefficient varies with runoff depth (as demonstrated by the figures presented in this report) is important and suggests that a single value for runoff coefficient may not be appropriate. Additional work is necessary to further investigate runoff coefficients for use with the rational method.

2. For simple watersheds, the rational method may be applied when only an estimate of the peak discharge from the runoff hydrograph is required. Watershed drainage area does not seem to be an important consideration. However, this observation must be tempered with a caveat that only 20 watersheds were examined. Furthermore, watershed complexity was not examined as part of this research. Because the rational method is a simple procedure, application of the method to a complex watershed would be an error of judgment and may result in substantial errors in estimated design discharge. Further study through expansion of the study database also is in order.

Therefore, the research proposed herein represents an important development of, and extension to, research already completed under TxDOT auspices.

2 Project Objectives

The objectives, as stated in the problem statement, are:

> The project objectives are to evaluate the appropriateness of using both rational and modified rational methods for small watershed design, evaluate the tabulated values of the runoff coefficient, and construct guidelines for TxDOT analysts for selection of appropriate parameter values for Texas watershed conditions.

Therefore, using the database developed by Asquith et al. (2004), supplemented with data added after publication of Asquith et al. (2004) for the Houston, Texas, region, an evaluation of the rational method and the modified rational method will be undertaken.

3 Implementation

The results of the proposed project are anticipated to include a number of implementable results. These include:

- Review of the range of applicability of the rational method and modified rational method
- Calibration and/or validation of rational method runoff coefficients for selected Texas watersheds
- An assessment of the utility of both the rational method and modified rational method for use in design of both drainage structures and best management practices

The above results are considered likely — additional results may come from the research. These results should be directly implementable by TxDOT and useful for providing guidance to TxDOT analysts involved in making estimates of hydrologic response for design activities.

4 Technical Approach and Work Plan

The technical approach and work plan for the proposed project is summarized in this section. The tasks approximately parallel project objectives described in Section 2. The major facets are

- Literature and database review
- Technical investigation of the rational method
- Assessment of results
- Reporting

Task 1: Literature and Database Review

As part of a previous TxDOT-supported research project (Project 0–4405), a literature review encompassing the rational method was completed (Thompson, 2004). Because a few years passed since execution and publication of that work, a review of the professional literature will be undertaken to either discover new publications pertinent to the project or ensure no new literature contributes knowledge to the problem.

A brief literature review is anticipated, partly because Thompson (2004) establishes much of the background for the rational method. However, a literature review is necessary to confirm a complete product.

Much of the existing database compiled for Texas is documented by Asquith et al. (2004). However, since publication of Asquith et al. (2004), additional data from 34 watersheds located in and around Houston, Texas were added. These events comprise 1094 rainfall-runoff events and significantly extend the database. Therefore, a review of the current database is considered appropriate to ensure data for recently-added watersheds are correct and complete.

A secondary objective of Task 1 is to locate additional rainfall-runoff measurements from very small watersheds (less than 1 square mile). Although location of additional watersheds is not considered critical, location in Texas would be considered ideal. The Agricultural Research Service (ARS) maintains a number of experimental watersheds across the United States. While their mandate differs from other researchers (ARS research is primarily concerned with agriculture), they do make measurements of rainfall-runoff responses from small watersheds. Therefore, contacts will be made in an effort to supplement the existing database, particularly for very small watersheds (drainage areas less than one square mile).

The research team has considerable experience with Texas hydrology and an existing collection of literature on relevant studies. In addition, members of the research team authored several papers on rainfall-runoff studies in Texas over the last decade. The literature review in this study will extend and complement the team's already sizeable literature collection.

A technical memorandum documenting results of Task 1 will be prepared and submitted on completion of this task.

Task 2: Technical Review of the Rational Method

Groundwork for studying the rational method (and modified rational method) was developed by Thompson (2007). Two principal threads of research seem reasonable: First take a more traditional approach to estimating runoff coefficients,

1. Extract estimates of the observed runoff coefficient (volumetric) from rainfall-runoff events in the database.
2. Compare table estimates of runoff coefficient with observed values of runoff coefficient.
3. Examine the relation between runoff coefficient and storm depth, if any.

The second approach is to take an entirely different track. Because the rational method is a rate-based method, it might be possible to extract estimates of a rate-based runoff coefficient from the project database. While the procedure remains to be refined, an approach is suggested that includes,

1. Extract peak discharges from the database; adjust to units of L/T.
2. Extract peak rainfall rates for the watershed time of concentration.
3. Estimate the rate-based runoff coefficient by dividing the discharge rate by the rainfall rate (equation 3).

A technical memorandum documenting results of Task 2 will be prepared and submitted on completion of this task.

Task 3: Assessment of Results

Substantial work on Texas rainfall depths (Asquith and Roussel, 2004) exists, as well as methods for estimating time of concentration (**?**). Given the database developed for Texas hydrologic research, it is possible to compare results derived from analysis of the database to produce estimates of the runoff coefficient with site-specific flood-frequency curves. The protocol for such comparisons could follow Thompson (2007), in which site-specific flood frequency curves (FFC) were developed from study watersheds and used as a baseline for assessment of study methods.

Possible comparisons include:

- Compute watershed time of concentration with methods presented in **?**.
- Use table runoff coefficients with existing approximations of the IDF relation to compute peak discharge. Compare with site-specific FFC.
- Use observed runoff coefficient with existing IDF curves to compute peak discharge. Compare with site-specific FFC
- Repeat the process with IDF curves derived from Asquith and Roussel (2004).

Other combinations may come from interactions of the research team with TxDOT project oversight personnel. The objective is to measure method performance in quantifiable terms. The approach is best developed in cooperation with research team and the project oversight team. This process has been fruitful in other completed projects.

A technical memorandum documenting results of Task 3 will be prepared and submitted on completion of this task.

Task 4: Reporting

Project reports are the principal deliverable for this project. Methods and materials used to execute the research and research results will be described by project research personnel and presented in a pair of reports. The final project report is intended for dissemination to TxDOT and other interested technical personnel; the project summary report is for wide distribution for publicizing TxDOT-supported research results.

Project researchers, not graduate students, will undertake report-writing tasks.

Information Technology

Computer programs may be developed and used during the conduct of the research. However, no computer program will be part of the deliverables for this project.

5 Assistance by TxDOT Personnel

No direct involvement of TxDOT personnel is expected or required to complete the proposed research. However, technical review and further input on project direction will be sought from the technical leaders within the TxDOT hydrologic community. It is understood that the broad mandate of the project requires continual discussions with TxDOT personnel to ensure that project results are readily used or adapted by design engineers of all experience levels.

6 Budget Summary

A budget summary for the participating institutions is presented below.[12]

Institution	FY 2008	FY 2009	FY 2010
UH	$50,000	$50,000	$20,000
USGS	$90,000	$90,000	$20,000
Lamar	$40,000	$40,000	$10,000
TxDOT Cost	$180,000	$180,000	$50,000
Total TxDOT Cost			$410,000

[12] UH portion includes professional services subcontract to R.O. Anderson for Dr. Thompson's involvement

7 Project Deliverables

Form DelTable
(Rev. 12/2006)
(GSD-EPC)

RTI
Deliverables Table
Project No. 0-6070

Note: Deliverables on this Table are not considered received by TxDOT until submitted to RTI.
See chapter 8 of the *Research and Implementation Manual* for standards for all deliverables.

Products: Minimum Stand-alone Products will be as specified on the **Project Statement** (Research Project) or **IPR** (Implementation Project). Examples of products typically most appropriate as stand-alone items include Guidebooks, Training Materials, Devices, Instruction Manuals, Brochures, and Software.

No.	Stand-Alone Product Description	Due Date (normally due at or before project termination)	Responsible Party for Joint Project (if blank, RS is assumed)	Comments
P1				

Reports: Minimum Reports will be as specified on the **Project Statement** (Research Project) or **IPR** (Implementation Project).

No.	Report Description (Succinctly describe intended contents of each report.)	Due Date (if blank, defaults to 60 days after project termination)	Responsible Party for Joint Project (if blank, RS is assumed)	Comments
R1	USGS SIR or WRIR Series Report	31 October 2009	RS	The product for this project, updated runoff coefficients, and intensity/depth adjustment procedures—if any, will be contained in report R1
PSR	Summary of work performed, findings and conclusions	31 October 2009	RS	

Date Updated:

Figure 5: Deliverable Table for 0-6070

8 Schedule of Research Activities

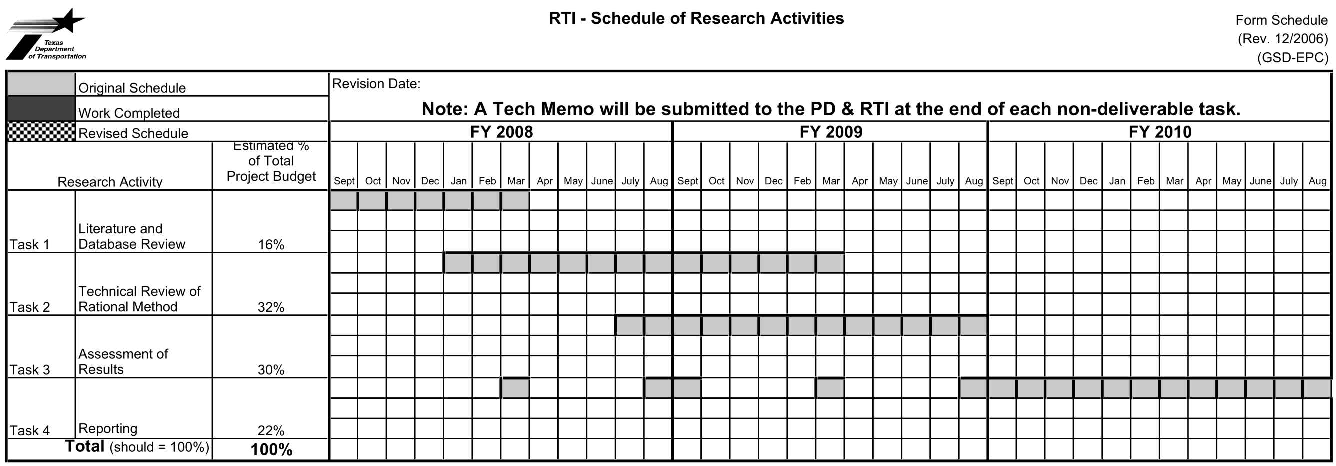

Figure 6: Project Schedule for 0-6070

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