**Use of the Basin Development Factor to Evaluate Urban Watershed Response**

Shiva Sunder[1], Theodore G. Cleveland[2], and David B. Thompson[3]

# 1. ABSTRACT

The Basin Development Factor ($BDF$) is a reasonably straightforward categorical variable that has promise for estimating urban hydrologic response. The objective of this study is exploratory — the goal is to learn whether the $BDF$ improves the explanation of the rainfall and runoff responses of watersheds. This particular metric is attractive as an alternative to other metrics in use.

The $BDF$ was determined for more than 100 watersheds in Texas and then used to generate estimates of unit hydrograph timing characteristics and peak discharge characteristics. Simulated responses using these values are compared to both observed and prior simulated responses for the same watersheds.

Inclusion of $BDF$ as an explanatory variable in the regression analyses in this study to generate hydrologic responses did not materially reduce, or enhance performance in models of selected watersheds. This finding indicates that use of $BDF$ cannot make estimates worse, but does not improve estimates either (and thus $BDF$ as implemented here could be ignored). The result was discouraging, but the particular effort overlooked that the regression models used could estimate zero discharges, when, in fact, the actual database did not contain zero values.

Despite the discouraging result, the authors believe that the BDF bears further study and suggestions for such studies are offered.

# 2. INTRODUCTION

Hydrologic response of a watershed is controlled in large part by its topography, storage properties, and loss (or runoff generation) properties. The study reported herein was motivated by an observation that topography is relatively unchanged in urban watersheds as they develop, but hydrologic response certainly changes — no doubt in some proportion to changes in storage, runoff generation, and conveyance efficiency to the outlet.

Liscum and Massey (1980), Liscum et al. (1996), and Liscum (2001) in a series of studies addressed the effect of change by a variety of watershed properties as explanatory variables

[1]Department of Civil and Environmental Engineering, University of Houston, Houston, Texas 77204-4003. email: ssunder@uh.edu
[2]Department of Civil and Environmental Engineering, Texas Tech University, Lubbock, Texas 79404-. email: theodore.cleveland@ttu.edu (corresponding author)
[3]R.O. Anderson Inc., 1603 Esmerelda Blvd., Minden, Nevada 89423. email: dthompson@roanderson.com

in rainfall-runoff regression models of the Houston area. One promising explanatory variable was the Basin Development Factor (*BDF*) (Sauer et al., 1983). The *BDF* is a measure of runoff transport efficiency of the drainage systems in a watershed, and thus indirectly addresses the storage and transport components of a watershed's runoff signal. *BDF* is a categorical variable, whose value is assigned based on the prevalence of certain drainage conditions that result from urbanization of a watershed.

Cleveland et al. (2008) used a particle tracking approach for parametrizing unit hydrographs from topographic information for selected watersheds in Texas. That work demonstrated that topographic information explained a large portion of variability in response, yet the use of a binary categorical variable for developed and undeveloped watersheds was insufficient to capture the spectrum of change as a watershed urbanizes; the *BDF* potentially extends the range of responses by 11 categories.

Southard (1986) examined an alternative urban basin characteristic, called the percentage developed area, to simplify the computation process of evaluating the percentage of impervious area within a basin. At the time, he speculated that the field reconnaissance of a watershed with an area of 20 square miles would take 1 to 6 hours but computation of percentage of developed area would take less than 2 hours for basins with area 22 square miles or less. Field reconnaissance necessary to determine BDF would be impractical if the user is located a considerable distance from the basin, however since that time tools like Google Earth make the prospect of computing a BDF as practical as percentage impervious area.

This study examines the *BDF* on urban hydrologic response. The objective of this research is to determine how the *BDF* explains the rainfall and runoff responses of watersheds and if this metric is a useful alternative to other metrics in use. The BDF is applied to more than 100 watersheds in Texas and the results compared to prior efforts on these watersheds.

## 3. METHODOLOGY

The database used for this research contains rainfall and runoff values, physical and dimensional parameters of 133 watersheds in Texas. The database combined the contents of Asquith et al. (2004) with recent computations of BDF using Google Earth, as well as recent additions to the original rainfall-runoff database.

The Basin Development factor is computed from analyst interpretation of the presence or absence of the following physical features, of which three (of four) are detectable using aerial imagery. Borrowing from Sauer et al. (1983) the four components and their meanings are:

(1) Channel Improvements: The improvements are noted by taking into consideration the phenomenon of straightening, deepening, clearing and enlarging. If all or any of the above phenomena are present in at least 50% of the main channel and its

tributaries, then, a value of one is given to the third of the watershed taken into consideration; else it takes the value zero.

(2) Channel linings: If more than 50% of the main channel length is lined with an impervious material like concrete, then a value of one is given to the third of the watershed under study, else the value of zero is assigned. Usually, if the drainage channel is lined with an impervious material, it will have a good channel improvement. Hence this aspect is an added factor to portray a highly developed drainage system.

(3) Storm drains or storm sewers: the enclosed drainage structures (usually pipes) that are used on the secondary tributaries, that collect the drainage from the parking lots, streets etc., and drain into open channels in most cases or into channels enclosed as pipe or box culverts are called storm drains. So, when over 50% of the secondary tributaries are found to have storm drains, then a value of one is given else zero value is given.

(4) Curbs and gutters: this factor reflects the actual urbanization of the watershed area. If more than 50% of the area is industrially developed or used in constructing residential or commercial buildings and if streets and freeways are constructed using curbs and gutters, then the value one is assigned. Else the value zero is given. Curbs and gutters take drainage to storm drains.

The authors acknowledge that storm sewers are likely undetectable from Google Earth imagery and thus there is considerable subjectivity in these last two components of the BDF, nevertheless the analysts proceeded using their best judgement to arrive at a defendable value.

The computation of BDF for one watershed is illustrated as an example. Figure 1 is a screen capture of a Google Earth image with a watershed delineated. The boundaries are approximate which is sufficient for this task.

The watershed is divided into three approximately equal parts that are examined for channel improvements, channel linings, storm drains and curbs and gutters. The component scores for the watershed are listed in Table 1. The upper portion of the watershed has no visible channel, thus these two components are scored zero. Storm sewers probably exist and are scored one on this conjecture and the obvious curb and gutter component is scored one in this portion. The middle portion has visible channels, and there is some evidence of improvement (there are linear features when the image is zoomed), but there is no visible evidence of lining. Hence the channel improvement is scored one, as is the curb and gutter, and storm sewer. The lower third has all components and each is scored one, for a total $BDF = 9$.

As an observation (from several dozens of urban watersheds) a $BDF = 9$ is a reasonably developed watershed. Several different analysts will arrive at different values of $BDF$ but

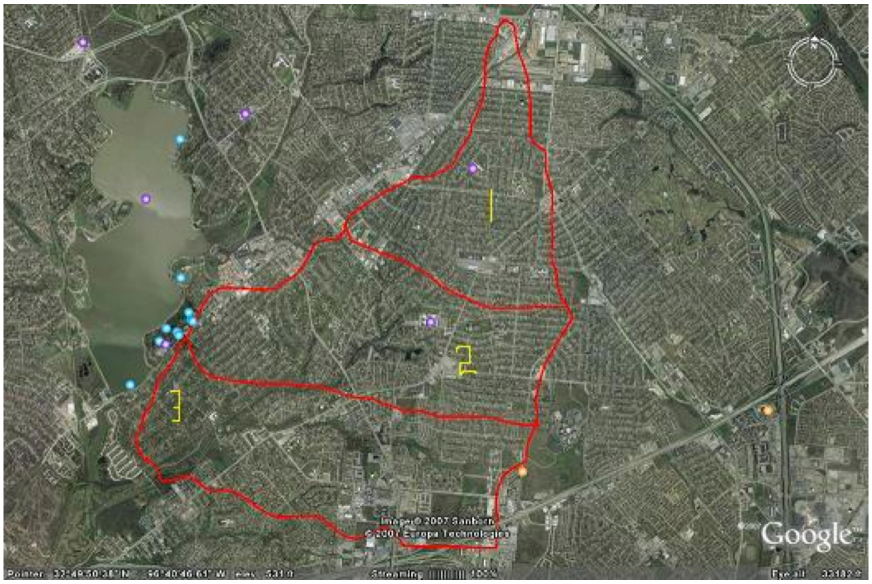


Figure 1. Station 0807320 Ashcreek Watershed, Dallas, Texas. Boundaries are approximate.

Table 1. Ash Creek BDF component scoring

| Area | Imp. Channel | Lined Channel | Storm Drain | Curb and Gutter |
|---|---|---|---|---|
| (1) Upper $\frac{1}{3}$ | 0 | 0 | 1 | 1 |
| (2) Middle $\frac{1}{3}$ | 1 | 0 | 1 | 1 |
| (3) Lower $\frac{1}{3}$ | 1 | 1 | 1 | 1 |

generally will be within a score of one, thus the subjectivity is not so large that two analysts will score at opposite ends of the scoring range.

Figure 2 is a plot of the relationship of a characteristic time, $T_p$, and a characteristic spatial dimension, $A/S_o$, for each watershed examined. The figure exhibits considerable variability, but when these results are segregated by *BDF* value, the watersheds with greater *BDF* value plotted closer to the lower envelope of the marker cloud (i.e. along the lower line in the figure), while the watersheds with lower *BDF* plotted along the upper envelope. This result is anticipated and important for the potential use of *BDF* as an explanatory variable[4].

The values of $T_p$ were determined from the observation data using methods described in Thompson et al. (2007) and Asquith et al. (2006) and can be considered metrics of the actual watershed response (as opposed to estimates obtained by regressions). The differences in the characteristic time were found to be meaningful enough to consider *BDF* as an explanatory, categorical variable. These values of *BDF* were then used to generate regression equations

[4]The differences are visible when the figure is plotted in color. The authors were unsure of the manuscript would be in color, so the text was written as if only black and white were available.

to estimate values of initial abstraction, $I_a$, loss rate, $C_l$, characteristic time to peak, $T_p$, and a peak rate factor, $Q_p$. The meanings of these values are analogous to the same terms used in the collective works of Cleveland et al. (2008), Thompson et al. (2007), Asquith and Roussel (2007), and Asquith et al. (2006).

Of particular importance, to reduce the effort required to analyze the database, station median values were used to generate the estimation equations that were used to generate the responses to rainfall input in the cases where $BDF$ was considered as an exploratory variable, while the other results presented herein were computed on a storm-by-storm basis.

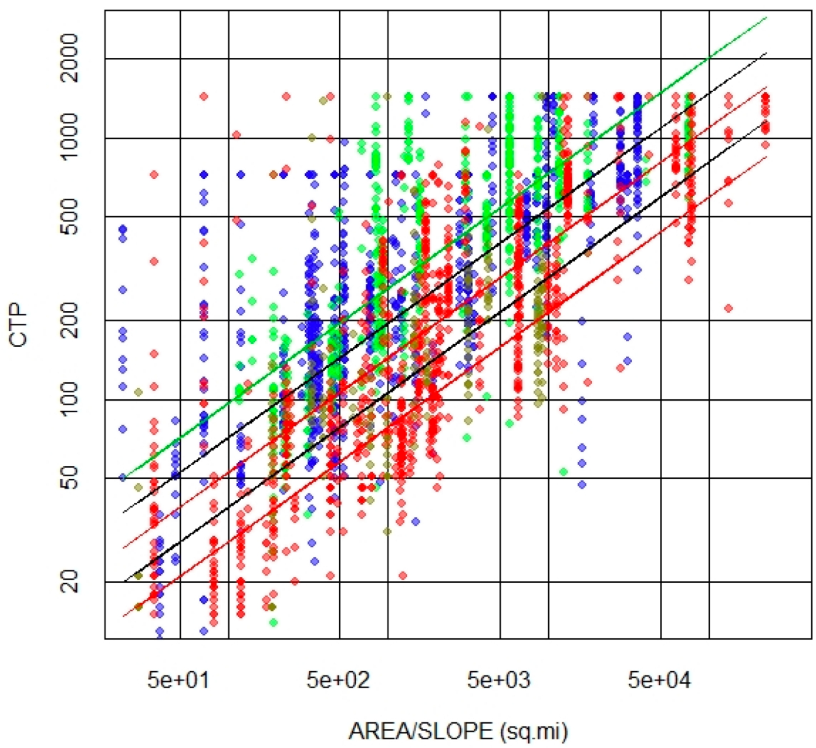


FIGURE 2. Observed characteristic time, $T_p$, and ratio of watershed area to slope (a characteristic spatial dimension) for all storms all watersheds. Markers indicate individual rainfall-runoff paired events. Marker density is indicative of relative number of markers in a particular location. Color is segregation by $BDF$ value.

Once these regression equations were generated, estimated responses from these regressions were compared with those of Asquith and Roussel (2007) where similar analysis was performed on a subset of these watersheds and Cleveland et al. (2008) where only a minimal set of categories related to basin development was examined. The desirable result would be a measurable reduction in variability explained by the additional categories; an undesirable result would be added variability, and a null result would be acceptable (but not particularly useful).

## 4. RESULTS

The *BDF* results presented here incorporate the loss model of Asquith and Roussel (2007), and only the characteristic time is different when comparing these two estimation procedures. The *NO_BDF* model uses the results from Cleveland et al. (2006), and represents storm-fitted unit hydrographs. The Digital Terrain Runoff Model (*DTRM*) results are from Cleveland et al. (2008) which incorporated a proportional loss model.

Figure 3 is a plot of the peak discharge values computed using the three different models. Ideally all models would plot along an equal value line. The markers representing the *BDF* model exhibit more variability than anticipated, but are still within reasonable values for most of the storms simulated.

Figure 4 is a plot of the time of peak discharge values computed using the three different models. Ideally all models would plot along an equal value line. Of particular note in this plot is the significant number of zero times in the *BDF* model. These values are attributed to the choice of loss model used in these simulations — and initial abstraction constant loss model that for some storms simulated zero runoff (when, in fact, actual runoff was non-zero). The markers representing the *BDF* model exhibit about the same variability as the prior efforts[5], and could be argued to reduce variability slightly.

The upper panel of Figure 3 is a boxplot of the information depicted in the scatterplots of Figure 3. The boxplots (and associated non-parametric tests) indicate that all the models perform the same when compared to each other or to their associated observations. Likewise the lower panel of figure 4 is a boxplot of the same information depicted in the scatterplots of Figure 4. These boxplots (and associated non-parametric tests) also indicate that all the models perform the same when compared to each other or to their associated observations.

## 5. DISCUSSION AND INTERPRETATION

Inclusion of *BDF* as an explanatory variable in a regression analysis to generate hydrologic responses did not materially reduce, or enhance performance in models of selected watersheds.

The implementation here was essentially an application of the loss models of Asquith and Roussel (2007) with an adjustment for the value of *BDF*, without re-analysis of the entire database — thus the method admits zero discharge cases when, in fact, such cases were not

[5]the zero values being ignored for this statement

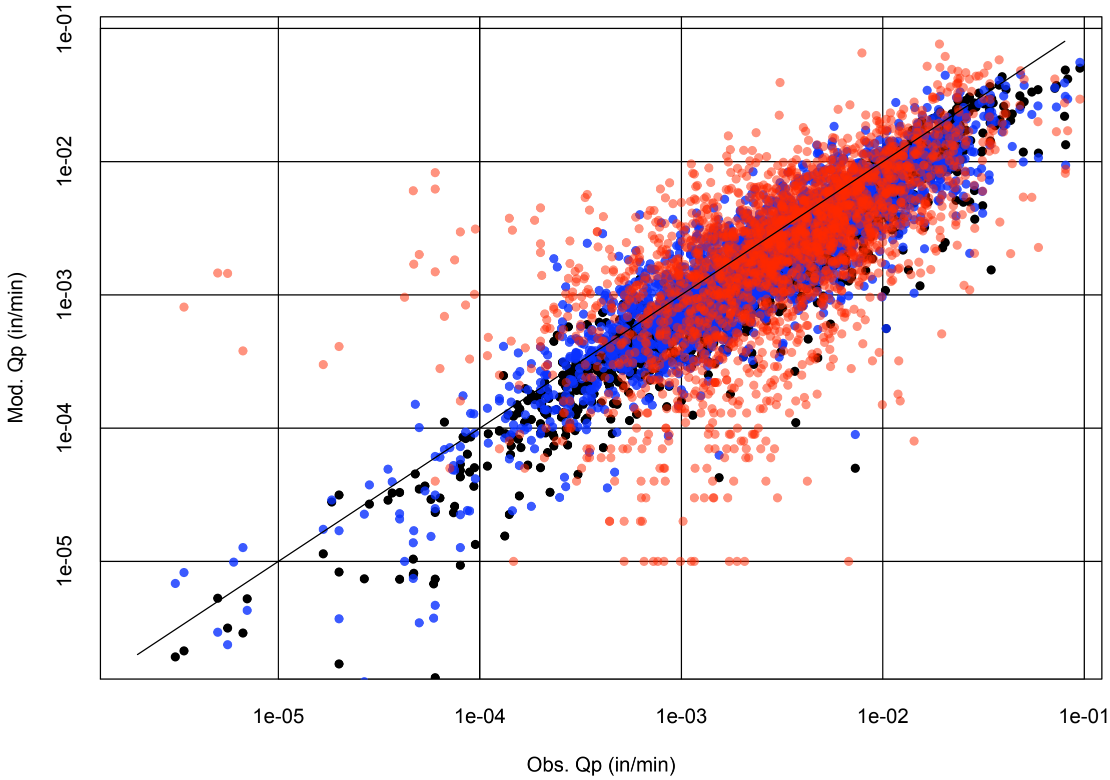


FIGURE 3. Plot of observed and model peak discharge values for individual storms on the study watersheds. Black markers (narrow marker cloud) are storm-optimized (storms fitted to unit hydrographs), blue circles are terrain-based unit hydrographs (Cleveland et al., 2008), and red markers are results estimated using a regression model that incorporates *BDF*.

in the original data, and this substantial difference is an issue needing further clarification. Furthermore, the authors did not re-analyze the entire database, instead choosing to apply regression to the station median values to incorporate the effects of *BDF* on response. This particular conceptual error is why the *BDF* did not perform as well as anticipated[6].

The simulated characteristic times, if the zero-discharge cases are censored, qualitatively reduces the variability in the responses, weakly supporting the original conjecture that *BDF* could confer additional accuracy in such modeling. Once loss (runoff generation) processes are accounted for, the simulated responses are sensitive to values of *BDF*.

[6]Or the BDF is simply not useful as an explanatory variable — yet its value in other venues suggests the conceptual error is a better explanation

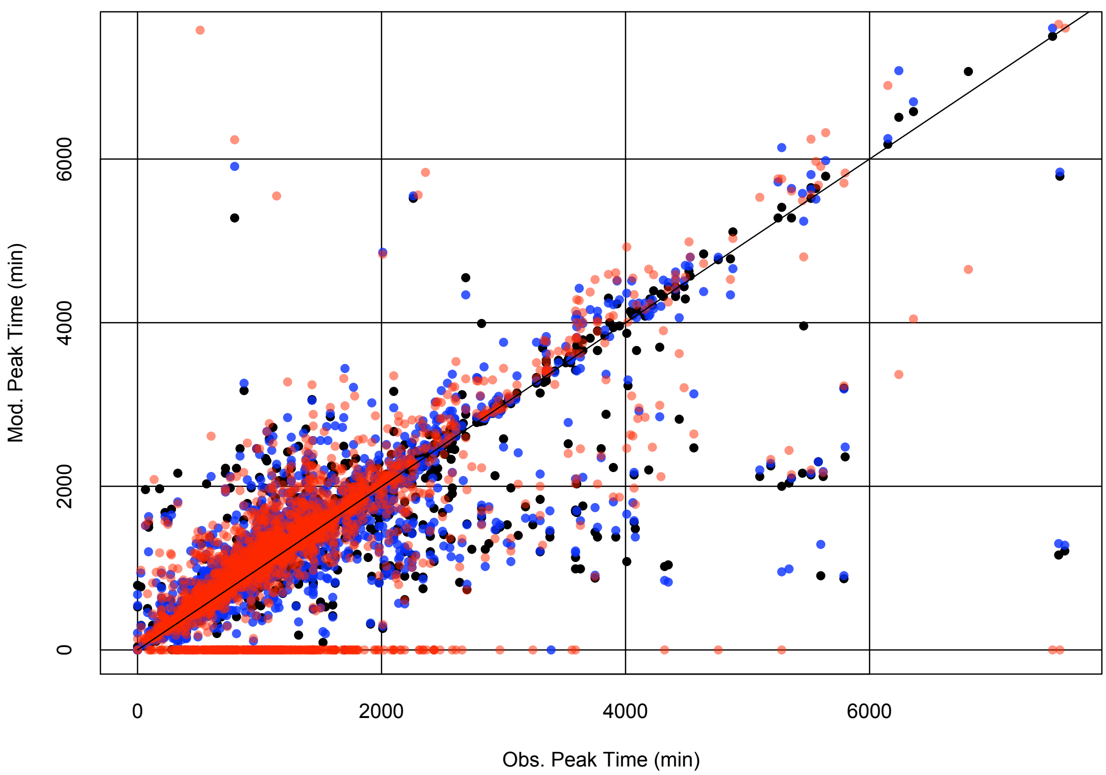


Figure 4. Plot of observed and model time of peak discharge values for individual storms on the study watersheds. Black markers (narrow marker cloud) are storm-optimized (storms fitted to unit hydrographs), blue circles are terrain-based unit hydrographs (Cleveland et al., 2008), and red markers are results estimated using a regression model that incorporates *BDF*.

Future efforts would be to re-analyze the entire database with *BDF* as an explicit explanatory variable (instead of a de-coupled analysis done in this work) and combine this effort with the terrain based model to determine if the inclusion of *BDF* improves the simulation value of that model. Additionally, the issue of runoff generation appears to be the crux of these kind of simulations and this issue is not adequately addressed in this work.

## 6. Acknowledgements

The research reported herein was supported in part by the Texas Department of Transportation and the Harris County Flood Control District. Their financial support is greatly appreciated and acknowledged.

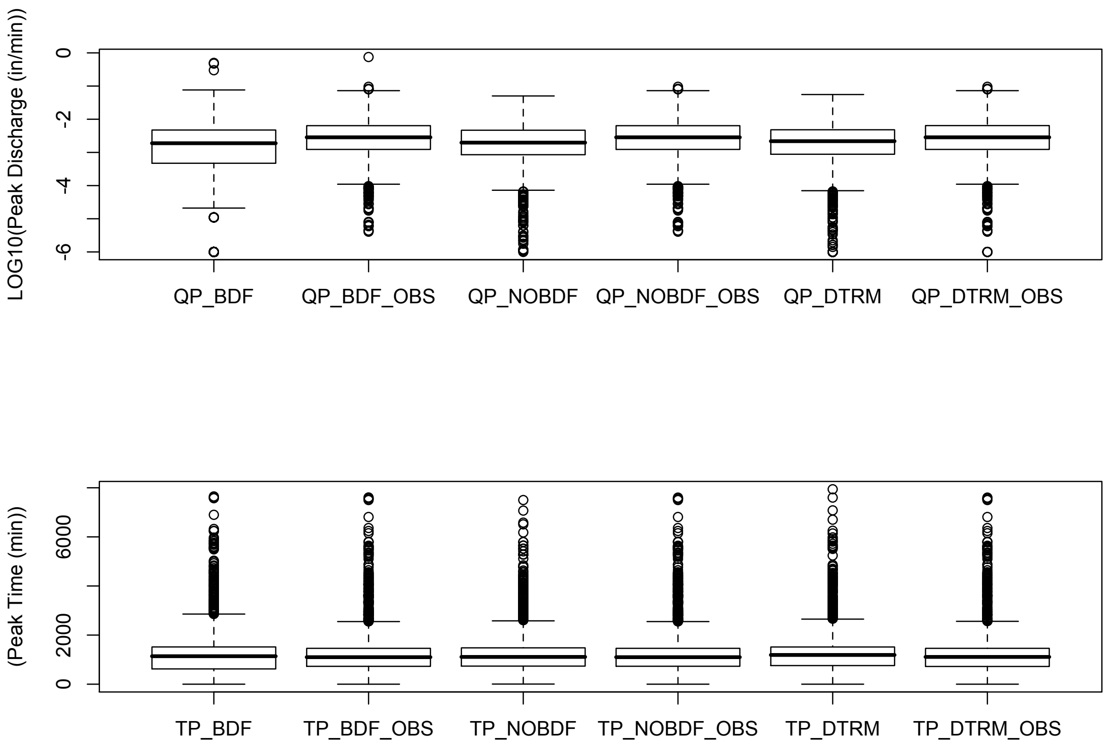


Figure 5. Upper Panel: Boxplot of the peak discharge for the three models (BDF, NO_BDF, and DTRM) and their respective observed (paired) values.

Lower Panel: Boxplot of the time of peak discharge for the three models (BDF, NO_BDF, and DTRM) and their respective observed (paired) values.

The authors further wish to acknowledge the guidance of their colleagues who contributed to this effort: G. R. Herrmann (Texas Department of Transportation) , T. Luong (Texas Department of Transportation) , W. H. Asquith (U.S. Geologic Survey) , M. S. Roussel (U.S. Geologic Survey), F. Liscum (PBS&J) , S. Johnson (LJA) , D. Schwertz (Natl. Weather Service) . and D. Barrett (R.G. Miller).

## References


Asquith, W. H. and M. C. Roussel (2007). An Initial-Abstraction, Constant-Loss Model for Unit Hydrograph Modeling for Applicable Watersheds in Texas. Scientific Investigations Report SIR 2007-5243, U.S. Geological Survey.

Asquith, W. H., D. B. Thompson, T. Cleveland, and X. Fang (2004). Synthesis of Rainfall and Runoff Data Used for Texas Department of Transportation Projects 0-4193 and 0-4193. Open-File Report OFR 2004-1035, U.S. Geological Survey.

Asquith, W. H., D. B. Thompson, T. G. Cleveland, and X. Fang (2006). Unit hydrograph estimation for applicable Texas watersheds. Research Report TechMRT/TxDOT 0-4193-4, Texas Department of Transportation.

Cleveland, T. G., X. He, W. H. Asquith, and D. B. Thompson (2006). Instantaneous Unit Hydrograph Evaluation for Rainfall-Runoff Modeling of Small Watersheds in North and South Central Texas. *ASCE J. of Irrigation and Drainage Engineering 132*(5), 479–485.

Cleveland, T. G., D. B. Thompson, X. Fang, and X. He (2008). Synthesis of Unit Hydrographs from Digital Elevation Model. *ASCE J. of Irrigation and Drainage Engineering 134*(2), 212–221.

Liscum, F. (2001). Effects of Urban Development on Stormwater Runoff Characteristics for the Houston, Texas, Metropolitan Area. Water-Resources Investigations Report 01-4071, U.S. Geological Survey.

Liscum, F., D. Brown, and M. Kasmarek (1996). Summary of Surface-Water Hydrologic Data for the Houston Metropolitan Area, Texas, water years 1964 – 89. Open-File Report 96-250, U.S. Geological Survey.

Liscum, F. and B. Massey (1980). Technique for Estimating the magnitude and Frequency of Floods in the Houston, Texas, Metropolitan Area. Water-Resources Investigations Report 80-17, U.S. Gelogical Survey.

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

Southard, R. E. (1986). An Alternative Basin Characteristic for use in Estimating Impervious Area for Urban Missouri Basins. Water-Resources Investigations Report WRIR 86-4362, U.S. Geological Survey.

Thompson, D. B., T. Cleveland, and X. Fang (2007). Loss Rate Functions for Selected Texas Watersheds. Research Report TechMRT/TxDOT 0-4193-5, Texas Department of Transportation.