

Instantaneous Unit Hydrograph Evaluation for Rainfall-Runoff Modeling of Small Watersheds in North and South Central Texas.

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ABSTRACT:

Data from over 1,600 storms at 91 stations in Texas are analyzed to evaluate an instantaneous unit hydrograph (IUH) model for rainfall-runoff models. The model is fit to observed data using two different merit functions: a sum of squared errors function (SSE), and an absolute error at the peak discharge time ( $Q_p$ MAX) function. The model is compared to two other models using several criteria. Analysis suggests that the Natural Resources Conservation Service Dimensionless Unit Hydrograph, Commons' Texas hydrograph, and the Rayleigh IUH perform similarly. As the NRCS and Commons' models are tabulations, the Rayleigh model is an adequate substitute when a continuous model is necessary. The adjustable shape parameter in the Rayleigh model does not make any dramatic improvement in overall performance for these data, thus fixed shape hydrographs are adequate for these watersheds.

KEY TERMS: unit hydrograph; rainfall-runoff models; Texas rainfall-runoff data.

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## INTRODUCTION:

The instantaneous unit hydrograph (IUH) is the direct runoff hydrograph (DRH) resulting from a unit depth of an excess rainfall hyetograph (ERH) applied uniformly over a watershed for a short ( $dt \rightarrow 0$ ) duration. A major advantage of an IUH is that the IUH does not require uniform excess precipitation for a specific duration.

The direct runoff hydrograph is computed as the convolution of the ERH and the IUH function as described by Equation 1.

$$Q(t) = A \int_0^t i(\tau)u(t-\tau)d\tau \quad [\text{Eqn. 1}]$$

where,

$i(t)$  is the EPH (precipitation rate as a function of time),  $u(t)$  is the IUH (unit response rate as a function of time),  $Q(t)$  is the DRH (direct runoff rate as a function of time),  $A$  is the watershed area, and  $\tau$  is a time lag (time between a particular precipitation event and its associated runoff).

The IUH function is required to exhibit linearity with respect to effective precipitation and integrates to unity; these are each properties shared by probability distributions. The similarity is not coincidental, and one interpretation is that the IUH is a residence time distribution of precipitation on the watershed.

Nash (1958), Leinhard (1964), Dooge (1973), and others, through conceptual approaches ranging from cascade of linear reservoirs to statistical-mechanical methods, have derived various IUH functions from observed DRH and ERH. Many of these IUH functions are

gamma-family probability distributions. Singh (2000) developed methods to represent the Natural Resources Conservation Service (NRCS) dimensionless unit hydrograph as a gamma distribution (Singh, 2000).

In this paper a gamma-family distribution for the IUH functions is tested using over 1,600 storms on 91 watersheds in North and South central Texas. The analysis determined distribution parameters for each storm, and compared the IUH model to conventional hydrograph models for applicability to the Texas data.

#### DATA ASSEMBLY AND PREPARATION:

The United States Geologic Survey (USGS) conducted small watershed studies in Texas during the period spanning the early 1960s to the middle 1970s. The storms documented in the USGS studies were used to evaluate unit hydrographs and these data are critical for unit hydrograph investigations in Texas. A substantial database was assembled from stations with paired rainfall and runoff data. Asquith et. al. (2004) provide details of the studies and database used in this paper.

The stations used in this paper are listed in Table 1. The table lists the USGS station number, common watershed or river basin name, the nominal drainage area, and the number of paired events. The rainfall and runoff data for each station were assembled into file-pairs (rainfall file and runoff file for each storm).

[Table 1 near here]

The over 1600 file pairs were parsed to extract the date/time, accumulated runoff, and accumulated weighted precipitation. In all cases, an artificial record was added so that all the data start at 00:00:00 of the event day. These files were further processed using linear interpolation to produce time-series of cumulative precipitation and runoff on one-minute increments. The one-minute interval was selected because the analysis follows the method described by Weaver (1993) and attributed to O'Donnell (1960), where each rainfall increment is treated as an individual storm and the runoff from these individual storms are convolved using a unit hydrograph to produce the model of the observed storm. The underlying data for rainfall and runoff are from larger time intervals, typically in the range of 5 to 15 minutes, and the one-minute resolution in these derived time-series is artificial.

A constant discharge baseflow separation method was used because it is simple to automate and apply to hydrographs with multiple peaks. Prior researchers (e.g. Laurenson and O'Donnell, 1969; Bates and Davies, 1988) have reported that unit hydrograph derivation is insensitive to baseflow separation method when the baseflow is a small fraction of the flood hydrograph – a situation satisfied in this work. The implementation determined when a rainfall event began on a particular day, all discharge before that time was accumulated and converted into an average rate. This average rate was then removed from the observed discharge data, and the remaining flow was considered to be direct runoff.

Excess precipitation was modeled using a constant fraction loss model (McCuen, 1998), where some constant ratio of precipitation becomes runoff. This approach again was selected for simplicity with regards to automated analysis. This loss model is represented as

$$\begin{aligned} \{i(t)\} &= C_r p(t) \\ C_r &= \frac{\int Q(t)dt}{A \int p(t)dt} \end{aligned} \quad [\text{Eqn 2}]$$

where

- $\{i(t)\}$  = excess rainfall rate.
- $p(t)$  = raw (observed) rainfall rate.
- $C_r$  = fraction of precipitation that appears as runoff
- $A \int p(t)dt$  = cumulative rainfall for the storm (a volume);  $A$  is watershed area.
- $\int Q(t)dt$  = cumulative direct runoff for the storm (a volume)

Additional details of the data preparation, separation techniques, and rainfall loss models are reported in He (2004).

#### HYDROGRAPH MODELS:

Three different hydrograph models are examined in this paper; the NRCS dimensionless hydrograph, the Commons hydrograph, and an IUH based on the Rayleigh distribution.

The NRCS Dimensionless Unit Hydrograph (DUH) used by the NRCS (formerly the SCS) was developed in the late 1940s (NRCS, 1985). The NRCS analyzed a large number of unit hydrographs for watersheds of different sizes and in different locations

and developed a generalized dimensionless unit hydrograph in terms of  $t/t_p$  and  $q/q_p$  where,  $t_p$  is the time to peak. The point of inflection on the unit graph is approximately 1.7 the time to peak and the time to peak was observed to be 0.2 the base time (hydrograph duration) ( $T_b$ ).

Commons (1942) developed a dimensionless unit hydrograph for use in Texas, but details of how the hydrograph were developed are not reported. The labeling of axes in the original document indicates that the hydrograph is dimensionless (i.e. units of flow and units of time). Figure 1 is a plot of the Commons hydrograph in its original units. The markers are the manually digitized values, obtained from the original figure (shown as the background) in Figure 1. A dimensionless hydrograph is created by dividing the ordinates of the Commons hydrograph by its peak units of flow value, and by dividing the units of time by the time when the peak occurs. In contrast to the NRCS hydrograph, the inflection point occurs at about  $2.0t_p$ , and the time to peak occurs at about  $0.13T_b$ .

[Figure 1 near here]

He (2004) developed several instantaneous unit hydrographs based on Gamma-family distributions following the conceptual approach of Nash (1958) and others. The behavior of a single reservoir element was postulated, then the elements were combined in a cascade structure and the behavior of this structure was analyzed to develop hydrograph distributions. Equation 3 is the Rayleigh instantaneous unit hydrograph.

$$u(t) = \frac{2}{t} \left( \frac{t}{\bar{t}} \right)^{2N-1} \left( \frac{1}{\Gamma(N)} \right) \exp\left(-\left(\frac{t}{\bar{t}}\right)^2\right) \quad [\text{Eqn 3}]$$

where

$\bar{t}$  = a distribution residence time

$N$  = reservoir number (a shape parameter)

Equation 3 is a special case of the hydrograph distribution developed by Leinhard (1964) and Leinhard and Meyer (1967) who postulated the distribution entirely from statistical-mechanical principles, then demonstrated its applicability on two watersheds in Iowa.  $N$  can take non-integer values (Nauman and Buffham, 1983), although the concept of a fractional reservoir has little physical analogy.

The Rayleigh hydrograph can be expressed as a dimensionless hydrograph using conventional terms by the following transformations.

$$T_p^2 = \frac{(2N-1)}{2} \bar{t}^2 \quad \text{[Eqn 4]}$$

$$Q_p = F * u(T_p) * A \quad \text{[Eqn 5]}$$

where

$T_p$  = time to peak (conventional meaning)

$Q_p$  = peak discharge rate (conventional meaning)

$A$  = watershed area

$F$  = unit conversion (e.g. 645.33 if  $u(T_p)$  is in inches/hour and  $A$  is square miles.)

The peak rate from Equation 3 is obtained from

$$u(T_p) = \frac{(2N-1)^N}{2^{N-1} \Gamma(N)} \frac{1}{T_p} \exp\left(-\frac{(2N-1)}{2}\right) \quad \text{[Eqn 6]}$$

and the dimensionless unit hydrograph is expressed as

$$\frac{u(t)}{u(t_p)} = \left(\frac{t}{t_p}\right)^{2N-1} \exp\left(-\left(\frac{t_p^2 - t^2}{2t_p^2}(2N-1)\right)\right) = \left(\frac{t}{t_p} \exp\left\{\frac{1}{2}\left(1 - \frac{t^2}{t_p^2}\right)\right\}\right)^{2N-1} \quad [\text{Eqn 7}]$$

Equation 4 relates the shape and residence time to the time to peak,  $T_p$ , with its conventional meaning, and Equation 5 is the peak discharge,  $Q_p$ , also with its conventional meaning. Equation 6 is the peak rate (of the Rayleigh distribution), and Equation 7 is a dimensionless representation of the instantaneous unit hydrograph.

[Figure 2 near here]

Figure 2 is a plot of the three hydrographs in dimensionless space. The Commons hydrograph is quite different in shape after the peak than the other dimensionless hydrographs -- it has a very long time base on the recession portion of the hydrograph. The Rayleigh hydrograph has adjustable shape in our work, but otherwise is more similar to the NRCS hydrograph than to the Commons hydrograph.

The Rayleigh rainfall-runoff model for this paper is the convolution of Equation 2 and Equation 3.

$$Q(t)_m = \int_0^t \{i(\tau)\} A \frac{2}{\bar{t}} \frac{1}{\Gamma(N)} \left(\frac{(t-\tau)^{2N-1}}{\bar{t}^{2N-1}}\right) \exp\left(-\left(\frac{(t-\tau)}{\bar{t}}\right)^2\right) d\tau \quad [\text{Eqn 8}]$$

In the case of either the NRCS or Commons hydrograph the unit hydrograph component is computed by the appropriate tabulation and dimensionalization ( $Q_p, T_p$ ).



## DETERMINING THE PARAMETERS

The resulting rainfall-runoff models require one or two parameters:  $T_p$  for NRCS and Commons models, and  $N$ , and  $\bar{t}$  for the Rayleigh model. The excess rainfall is determined by the storm properties. The parameters for each storm are determined by calculating the direct runoff hydrograph from Equation 8 using the observed rainfall and comparing the modeled response to the observed response for the same storm on the same watershed. Two different merit functions considered were the sum of squared errors (SSE) and a maximum absolute deviation at peak discharge ( $Q_pMAD$ ). Mathematically these merit functions are represented as

$$SSE = \sum_{i=1}^{NOBS} (Q_m - Q_o)_i^2 \quad [\text{Eqn 9}]$$

and

$$Q_pMAD = |Q_m(t_{peak}) - Q_o(t_{peak})| \quad [\text{Eqn 10}]$$

where  $Q$  is the discharge ( $L^3/T$ ); the subscripts  $O$  and  $M$  represent observed and model discharge;  $NOBS$  is the total number of values in a particular storm event;  $t_{peak}$  is the actual time in the observations when the peak observed discharge occurs. The first merit function produces results that sacrifice peak matching in favor of matching the runoff volume, while the second merit function is favors matching the peak discharge magnitude with little regard for the rest of the hydrograph. A search technique was used instead of more elegant methods, principally to ensure a result. The search systematically computes the value of a merit function using every permutation of model parameters described by the set-builder notation in Equation 11.

Rayleigh model :

NRCS and Commons model :

$$\bar{t} \in \{1,2,3,\dots,720\}$$

$$N \in \{1.00,1.01,1.02,\dots,9.00\}$$

$$T_p \in \{1,2,3,\dots,720\}$$

[Eqn 11]

Fractions of a minute were ignored (hence the one-minute increments in the timing parameters) and higher resolution in the shape parameter was deemed unnecessary. The set of parameters that produces the smallest value of the merit function is saved as the storm optimal set for that storm. This approach, while inelegant, is robust and produces values that are qualitatively reasonable.

## TYPICAL RESULTS

Figure 3 is a plot of a typical result. The figure compares the model hydrograph and the observed hydrograph for a particular storm. Qualitatively this plot suggests that all the models produce different, but comparable results. For the particular example in Figure 3, the Rayleigh model appears to perform better with regards to peak fit than the other models, but this better performance does not generalize to the entire set of storms.

Figure 4 is a plot of the peak discharge produced by Equation 8 for each storm versus the observed peak discharge for that storm for the three models. Figure 4 is for parameters based on the SSE merit function. The solid line is the 1:1 line along which all the markers should plot. The figure illustrates that the SSE merit function marker cloud falls below the 1:1 line and thus generally under-predicts peak magnitudes. The Rayleigh model has greater variability than either the NRCS or Commons model, and the NRCS

and Commons model produce very similar results despite their different appearance in dimensionless space.

Figure 5 is the same information as Figure 4 except the parameters are based on the  $Q_p$ MAX merit function. Figure 5 illustrates that the 1:1 line passes through the center of the marker cloud, with slightly more variability for all the models. Qualitatively this figure demonstrates that if peak discharge prediction is important, this merit function is preferred. This result is not surprising as the merit function compares differences in peak flows.

Figures 6 and 7 are plot of the time when the model peak discharge occurs (in dimensional time) versus the time when the observed peak discharge occurs (also in dimensional time). In both these figures the 1:1 line passes through the centroid of the marker cloud suggesting that either merit function is adequate for finding the timing parameter of any of the hydrograph models.

Figures 8 and 9 are plots of the dimensionless parameters  $Q_p$  and  $T_p$  for each storm plotted against watershed area. The Rayleigh model parameters are expressed in  $Q_p$  and  $T_p$  form using equations 4 and 5. The plots indicate that the stations have multiple storms, and illustrate the range of drainage areas used in this study (e.g. small watersheds). Trendlines in each figure are to illustrate that both the general trend of the marker clouds and the relative location of the cloud centroid are about the same for each hydrograph model.

## ACCEPTANCE ANALYSIS

We examined three measures of acceptability as a quantitative approach to determine if one of the three models performed better for these data. These measures are calculated after determining the parameters. The measures are a normalized mean square error, a peak discharge relative error, and a peak time absolute error.

Normalized mean square error emphasizes scatter in a data set. Smaller values of NMSE suggest better performance. NMSE is calculated (Patel and Kumar, 1998) using

$$NMSE = \frac{(\overline{Q_o - Q_m})^2}{\overline{Q_o} \overline{Q_m}}. \quad [\text{Eqn 12}]$$

Where  $\overline{Q_o}$  is the arithmetic mean of the observed runoff values, and  $\overline{Q_m}$  is the arithmetic mean of the model runoff values.

The peak relative error is the difference in magnitude between the observed and model peak rate and defined as

$$QB = (Q_{Po} - Q_{Pm}) / Q_{Po}. \quad [\text{Eqn 13}]$$

The peak temporal absolute error (TB) is the difference in arrival time of the largest runoff rate in the model results as compared to the observed results. It is calculated for each storm from

$$TB = t_{Po} - t_{Pm}. \quad [\text{Eqn 14}]$$

A TB less than zero indicates that the model predicts a late peak (i.e. real peak comes sooner). Whereas a positive value indicates that the model predicts an early peak.

The performance of an exact model (that is faithful reproduction of observations) is that the NMSE,  $QB$ , and  $TB$  should approach zero. Table 2 lists the median values of these measures for over 1600 storms.

[Table 2 near here]

Table 2 indicates that all the models produce similar values of the measures regardless of merit function. The NRCS and Rayleigh models perform somewhat better than the Commons model. A pragmatic approach based on concepts suggested by Hanna and Heinhold (1985), Patel and Kumar (1998), and Kumar and others (1999), is to specify acceptance ranges for the measures and count the number of storms that meet these criteria. In the present work we set the following ranges for  $QB$  and  $TB$ .

$$-0.25 \leq QB \leq 0.25 \quad \text{[Eqn 15]}$$

$$-30 \leq TB \leq 30 \quad \text{[Eqn 16]}$$

These values were selected ad-hoc as desirable tolerances for this analysis. The units of  $TB$  are minutes. Table 3 lists the fraction of storms for each merit function meeting the acceptance tolerances in Equations 15 and 16. Using this acceptance approach, again all the models perform similarly, with slight advantage to the Rayleigh model.

[Table 3 near here]

## CONCLUSIONS

The analysis presented in this paper indicates that the Rayleigh, Commons and NRCS hydrograph models produce comparable results for these data. The merit function used to

estimate parameters made a minor difference on overall performance. The SSE merit function is expected to produce hydrograph parameters that will underpredict the peak discharge as compared to the QpMAX criterion. This conclusion is supported by Figures 4 and 5 and by the difference in the median QB values for all analyzed storms.

The Rayleigh model is demonstrated to be an adequate substitute for the Commons and NRCS tabulations. It is expected that other Gamma-family models are also suitable substitutes. The adjustable shape parameter in the Rayleigh model did not produce any dramatic improvement on model performance, thus for these data the use of unit hydrographs with fixed shapes is adequate.

#### ACKNOWLEDGEMENTS

The research described in this paper was supported by the Texas Department of Transportation under project number 0-4193. The discussions and guidance of the project director George R. Herrmann, and the program coordinator David Stolpa are gratefully acknowledged. The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect official views or policies of the U.S. Department of Transportation, Federal Highway Administration or the Texas Department of Transportation. This paper does not constitute a standard, specification, or regulation.

The 1-minute derived data, IUH results, and plots for all the storms using all the models in this paper are publicly available at <http://cleveland1.cive.uh.edu> (129.7.204.231).

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Table 1. List of Stations, Drainage Area, and Storm Count.

Table 2. Acceptance measures for two merit functions and three unit hydrograph models.

Table 3. Fraction of storms within prescribed peak and temporal error criteria.

Table 1. List of Stations, Drainage Area, and Storm Count.

Austin			
Watershed	Area (km <sup>2</sup> )	Station ID	#Events
BartonCreek	232.31	08155200	5
BartonCreek	300.43	08155300	8
BearCreek	31.60	08158810	8
BearCreek	62.16	08158820	2
BearCreek	54.39	08158825	2
BoggyCreek	33.93	08158050	10
BoggySouthCreek	9.27	08158880	14
BullCreek	57.75	08154700	13
LittleWalnutCreek	13.52	08158380	2
OnionCreek	321.15	08158700	6
OnionCreek	429.92	08158800	2
ShoalCreek	7.23	08156650	13
ShoalCreek	18.21	08156700	16
ShoalCreek	19.58	08156750	13
ShoalCreek	31.86	08156800	24
SlaughterCreek	21.34	08158840	9
SlaughterCreek	59.83	08158860	2
WallerCreek	5.98	08157000	40
WallerCreek	10.70	08157500	38
WalnutCreek	14.43	08158400	10
WalnutCreek	31.34	08158500	14
WalnutCreek	32.63	08158100	15
WalnutCreek	67.86	08158200	17
WalnutCreek	132.86	08158600	22
WestBouldinCreek	8.08	08155550	10
WilbargerCreek	11.94	08159150	29
WilliamsonCreek	16.32	08158920	14
WilliamsonCreek	49.21	08158930	18
WilliamsonCreek	71.48	08158970	16

Dallas			
Watershed	Area (km <sup>2</sup> )	Station ID	#Events
AshCreek	17.92	08057320	5
BachmanBranch	25.90	08055700	39
CedarCreek	24.40	08057050	3
CoombsCreek	12.30	08057020	7
CottonWoodCreek	22.01	08057140	6
DuckCreek	20.85	08061620	8
ElamCreek	3.24	08057415	8
FiveMileCreek	19.81	08057418	7
FiveMileCreek	34.19	08057420	10
FloydBranch	10.80	08057160	8
JoesCreek	5.02	08055580	7
JoesCreek	19.45	08055600	10
NewtonCreek	15.31	08057435	4
PrairieCreek	23.39	08057445	8
RushBranch	3.16	08057130	7
SouthMesquite	34.70	08061920	9
SouthMesquite	59.57	08061950	31
SpankyCreek	17.53	08057120	5
TurtleCreek	20.67	08056500	42
WhitesBranch	6.55	08057440	4
WoodyBranch	29.78	08057425	10

Fort Worth			
Watershed	Area (km <sup>2</sup> )	Station ID	#Events
DryBranch	2.80	08048550	25
DryBranch	5.57	08048600	27
LittleFossil	14.61	08048820	19
LittleFossil	31.86	08048850	24
Sycamore	45.84	08048520	24
Sycamore	2.51	08048530	28
Sycamore	3.50	08048540	24
Sycamore	0.98	SSSC	21

San Antonio			
Watershed	Area (km <sup>2</sup> )	Station ID	#Events
AlazanCreek	8.44	08178300	30
LeonCreek	14.43	08181000	9
LeonCreek	38.85	08181400	15
LeonCreek	3.08	08181450	29
OlmosCreek	0.85	08177600	12
OlmosCreek	53.61	08177700	23
OlmosCreek	6.29	08178555	10
SaladoCreek	24.71	08178600	13
SaladoCreek	10.49	08178620	3
SaladoCreek	6.35	08178640	7
SaladoCreek	6.03	08178645	5
SaladoCreek	0.67	08178690	39
SaladoCreek	1.17	08178736	12

Small Rural Sheds			
Watershed	Area (km <sup>2</sup> )	Station ID	#Events
BrazosBasin/Cow Bayou	13.60	08096800	49
BrazosBasin/Green	8.24	08094000	28
BrazosBasin/Pond-Elm	57.50	08098300	19
BrazosBasin/Pond Elm	125.87	08108200	20
ColoradoBasin/Deep	8.86	08139000	25
ColoradoBasin/Deep	14.01	08140000	28
ColoradoBasin/Mukewater	56.46	08136900	22
ColoradoBasin/Mukewater	10.41	08137000	38
ColoradoBasin/Mukewater	182.33	08137500	4
SanAntonioBasin/Calaveras	18.16	08182400	23
SanAntonioBasin/Escondido	8.52	08187000	31
SanAntonioBasin/Escondido	21.83	08187900	21
TrinityBasin/Elm Fork	1.99	08050200	34
TrinityBasin/Honey	3.26	08058000	28
TrinityBasin/Honey	5.54	08057500	31
TrinityBasin/Little Elm	5.44	08052630	28
TrinityBasin/Little Elm	195.54	08052700	57
TrinityBasin/North	17.66	08042650	14
TrinityBasin/North	55.94	08042700	69
TrinityBasin/Pin Oak	45.58	08063200	33

Table 2. Acceptance measures for two merit functions and three unit hydrograph models.

Measure	Hydrograph Model		
	Commons	NRCS	Rayleigh
Median_NMSE_SSE	1.29E-07	4.09E-11	2.56E-10
Median_NMSE_PEAK	3.69E-09	2.75E-11	1.48E-14
Median_QB_SSE	0.38	0.34	0.29
Median_QB_PEAK	0.20	0.12	-0.08
Median_TB_SSE	-3.00	-6.00	-10.00
Median_TB_PEAK	20.00	19.00	2.00

Table 3. Fraction of storms within prescribed peak and temporal error criteria.

Measure	Hydrograph Model		
	Commons	NRCS	Rayleigh
QB_SSE	0.29	0.35	0.42
QB_PEAK	0.40	0.45	0.48
TB_SSE	0.59	0.57	0.56
TB_PEAK	0.54	0.52	0.62

Figure 1. Commons (1942) Texas unit hydrograph. Circles are from manual digitization of the original figure (shown in background). Used with Permission.

Figure 2. Commons, NRCS, and Rayleigh dimensionless hydrographs. The Rayleigh hydrograph is shown for two different values of  $N$  (shape parameter).

Figure 3. Typical results for a single storm using QpMAX merit function and three different hydrograph models. Station is located on Ash Creek in Dallas, Texas. Storm date is June 3, 1973.

Figure 4. Rayleigh, Commons, and NRCS model peak discharge versus observed peak discharge for parameters determined by the SSE criterion.

Figure 5. Rayleigh, Commons, and NRCS model peak discharge versus observed peak discharge for parameters determined by the QpMAX criterion.

Figure 6. Rayleigh, Commons, and NRCS model time of peak discharge versus observed time of peak discharge for parameters determined by the SSE criterion.

Figure 7. Rayleigh, Commons, and NRCS model time of peak discharge versus observed time of peak discharge for parameters determined by the QpMAX criterion.

Figure 8. Plot of  $T_p$  versus drainage area for study area. Trendlines are from OLS regression on log-transformed values.

Figure 9. Plot of  $Q_p$  versus drainage area for study area. Trendlines are from OLS regression on log-transformed values.

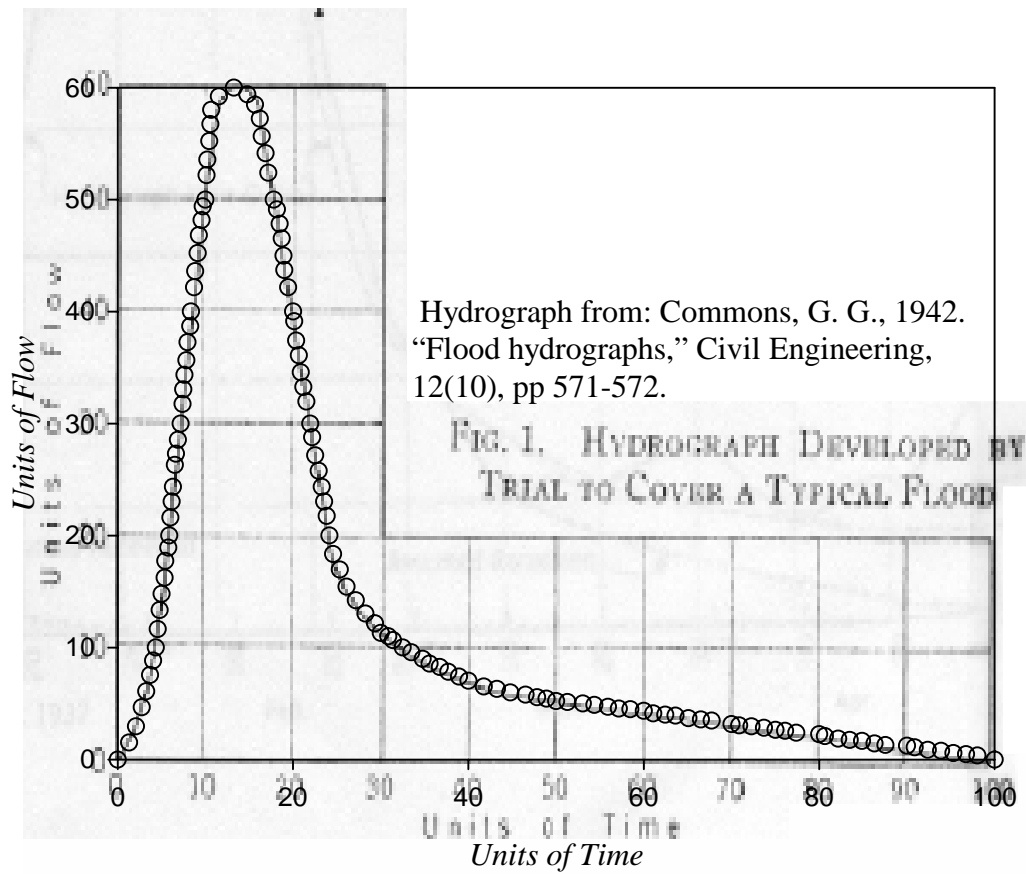


Figure 1. Commons (1942) Texas unit hydrograph. Circles are from manual digitization of the original figure (shown in background).  
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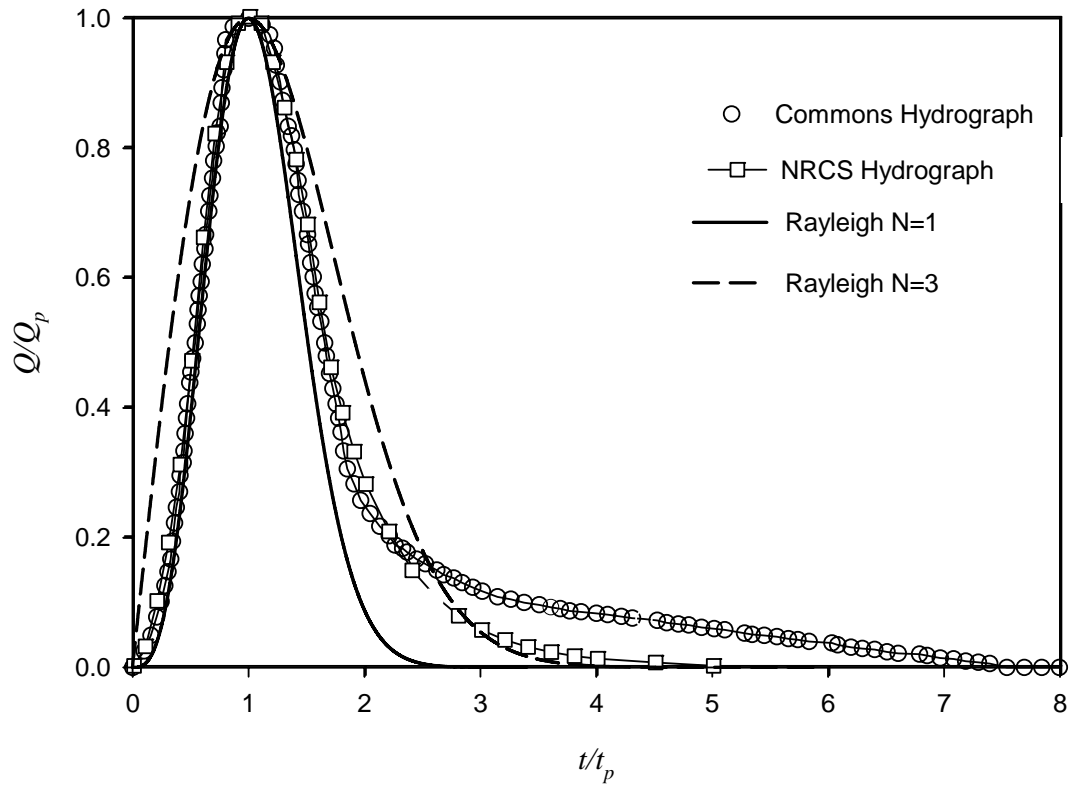


Figure 2. Commons, NRCS, and Rayleigh dimensionless hydrographs. The Rayleigh hydrograph is shown for two different values of  $N$  (shape parameter)

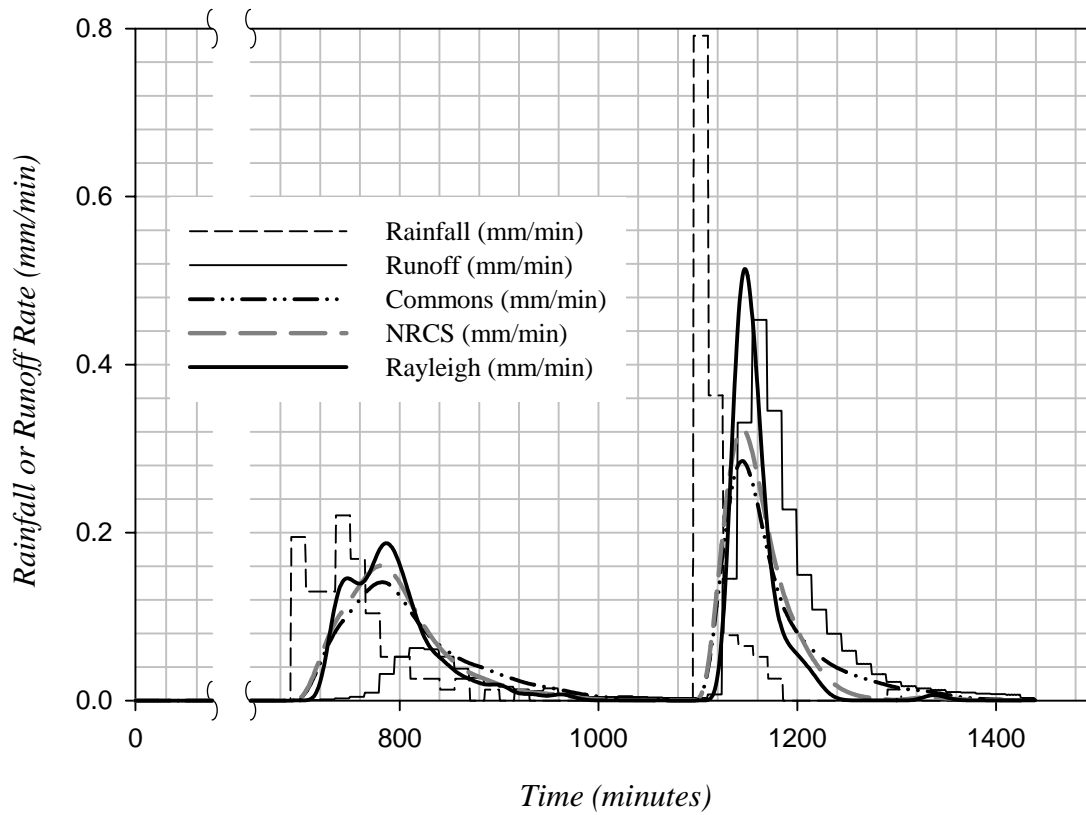


Figure 3. Typical results for a single storm using QpMAX merit function and three different hydrograph models. Station is located on Ash Creek in Dallas, Texas. Storm date is June 3, 1973.

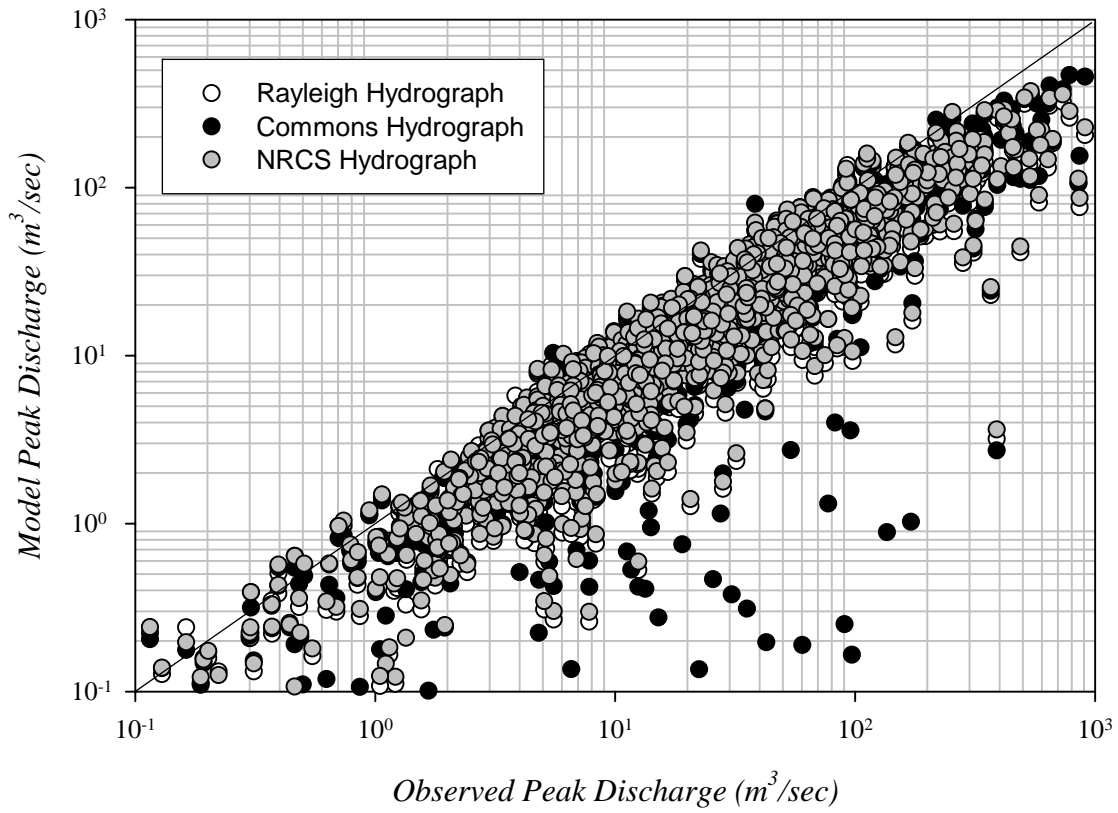


Figure 4. Rayleigh, Commons, and NRCS model peak discharge versus observed peak discharge for parameters determined by the SSE criterion.

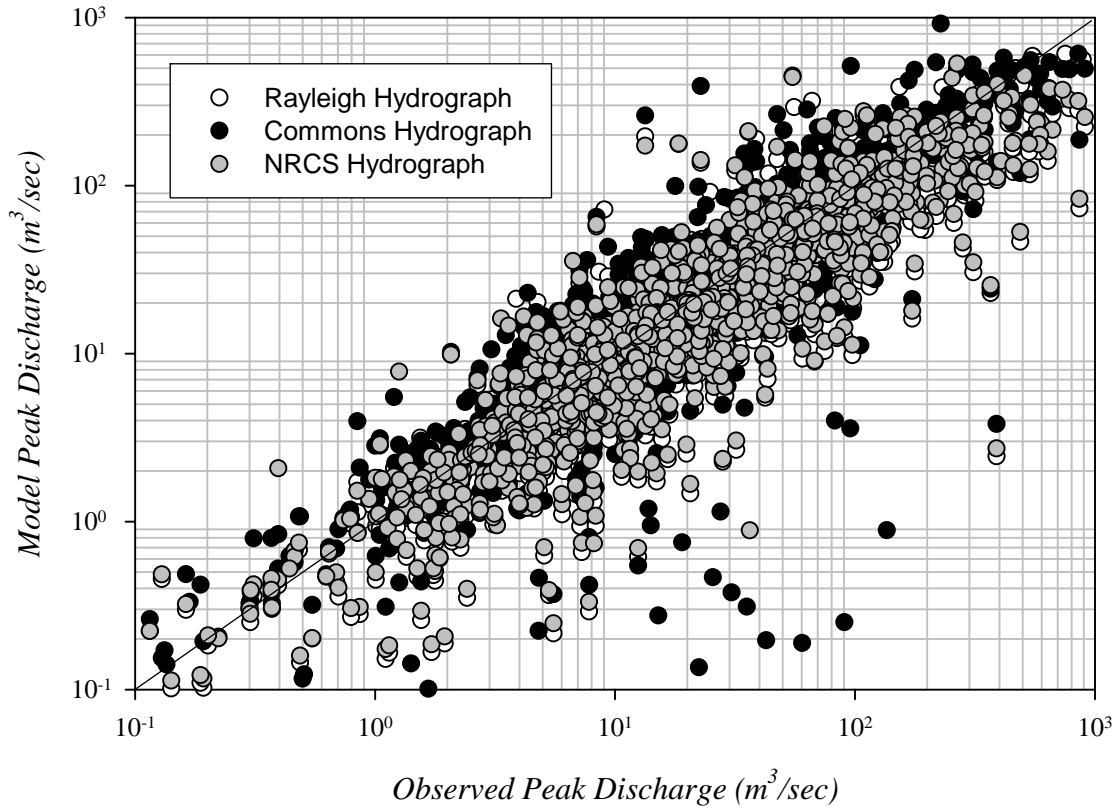


Figure 5. Rayleigh, Commons, and NRCS model peak discharge versus observed peak discharge for parameters determined by the QpMAX criterion.

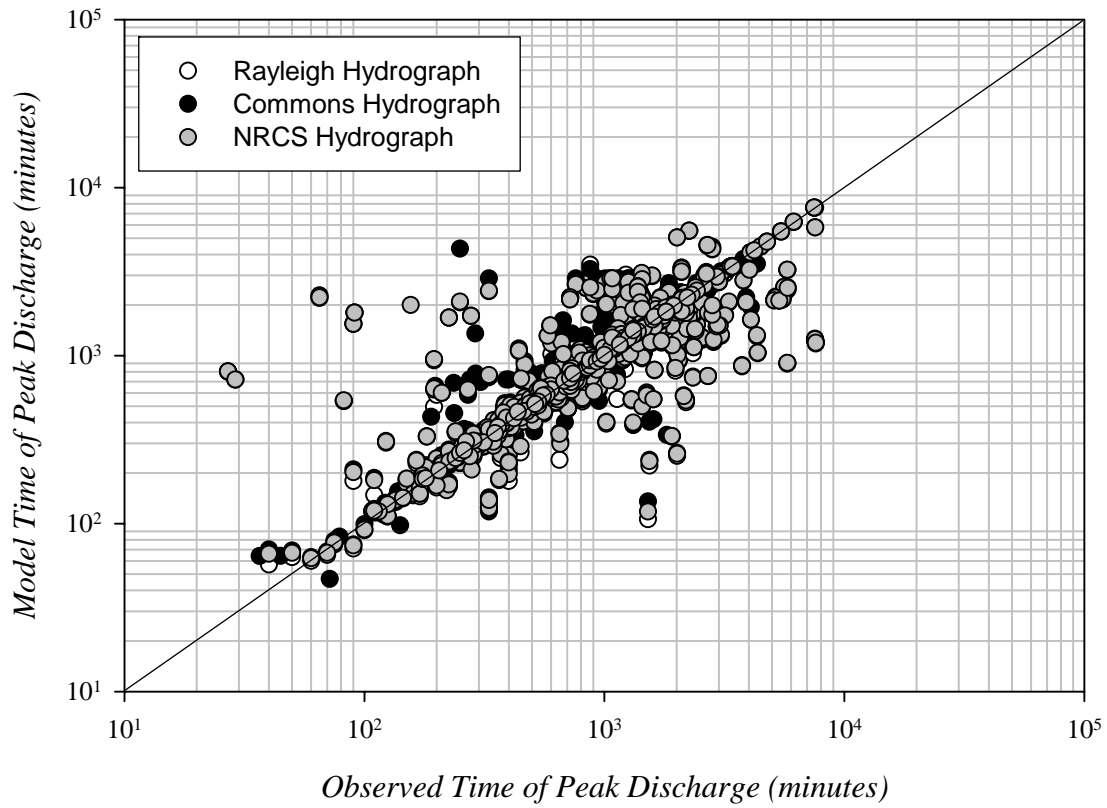


Figure 6. Rayleigh, Commons, and NRCS model time of peak discharge versus observed time of peak discharge for parameters determined by the SSE criterion.

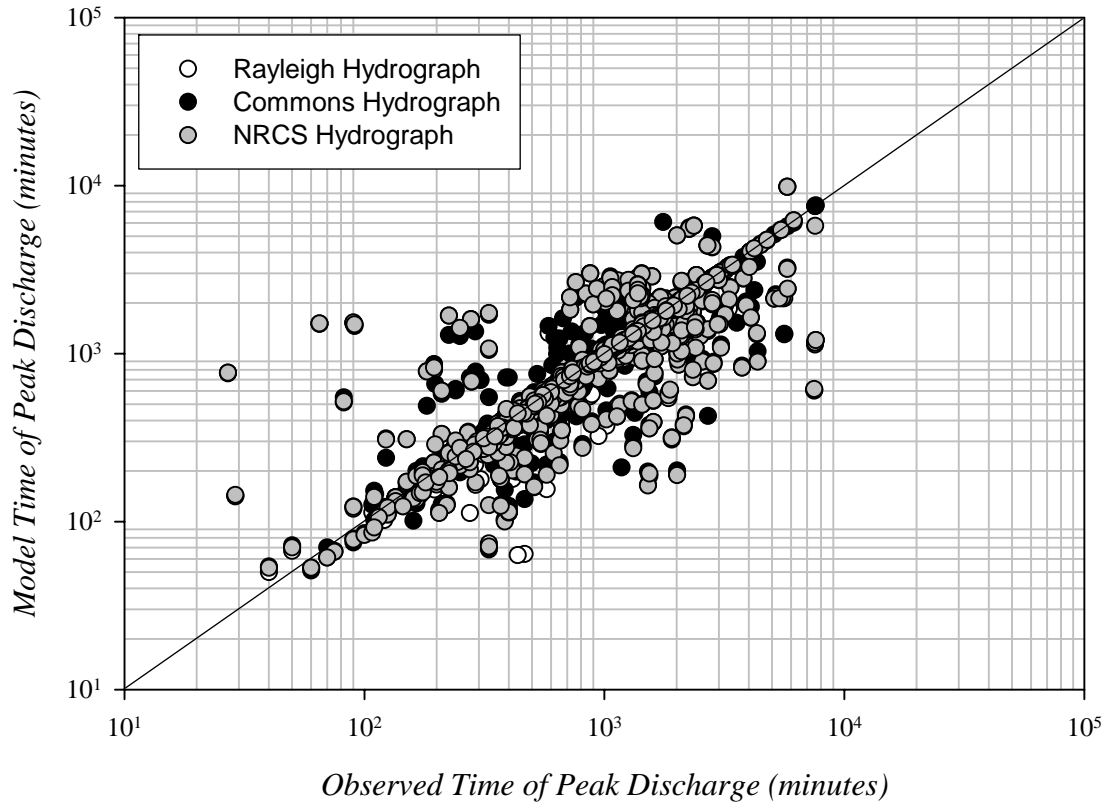


Figure 7. Rayleigh, Commons, and NRCS model time of peak discharge versus observed time of peak discharge for parameters determined by the QpMAX criterion.

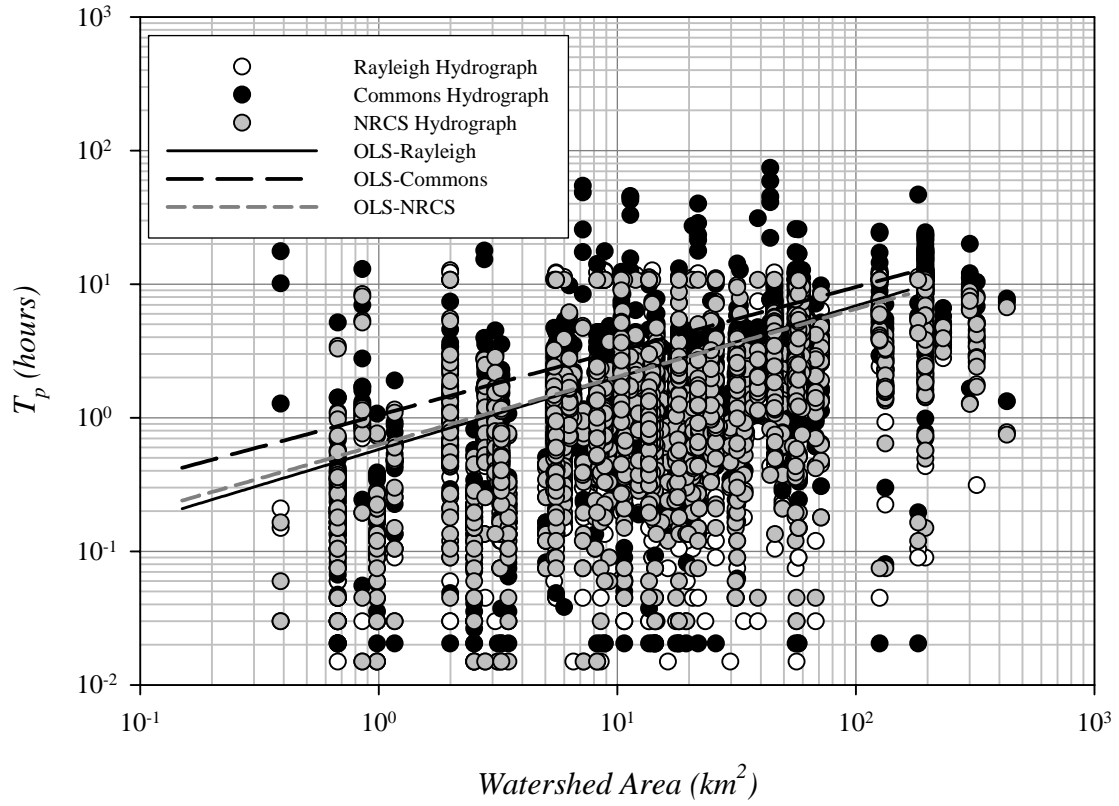


Figure 8. Plot of  $T_p$  versus drainage area for study area. Trendlines are from OLS regression on log-transformed values.

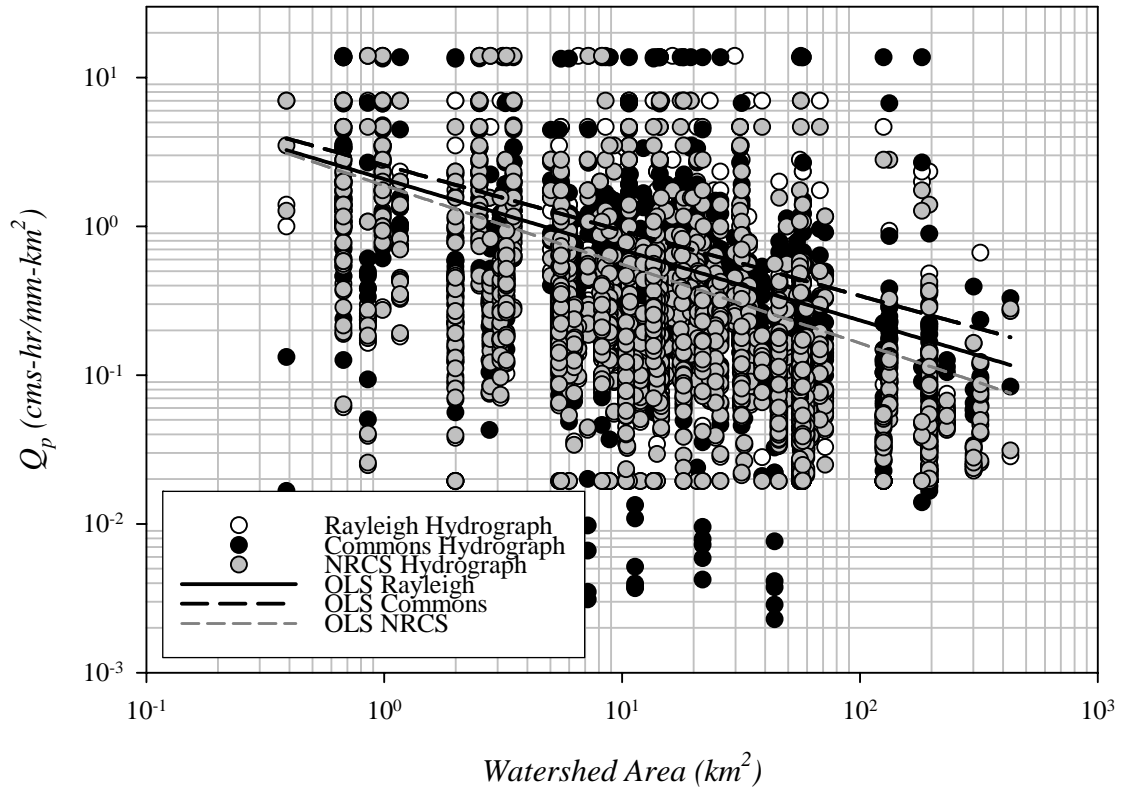


Figure 9. Plot of  $Q_p$  versus drainage area for study area. Trendlines are from OLS regression on log-transformed values.