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LAG TIMES AND PEAK COEFFICIENTS FOR RURAL WATERSHEDS IN KANSAS

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Lawrence, Kansas

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The recommended formula for the lag times of small rural watersheds in Kansas is

$$T_{lag} = 0.086 \cdot \left(\frac{L}{\sqrt{S}}\right)^{0.64}$$

for T_{lag} in hours, L in km and S in m/m. The variable L is the total length of the main channel, extended to the drainage divide. The variable S is the elevation difference between two points on the channel, located 10% and 85% of the channel length from the outlet, divided by the length of channel between the two points (0.75 L). This formula has a standard error of estimate of approximately 24%. It is applicable to watersheds with drainage areas up to 50 km^2. The peak coefficients for the unit hydrographs of the gaged watersheds range from 0.46 to 0.77, with a mean of value of 0.62 and a standard deviation of 0.10. The peak coefficient is not correlated significantly with any of the watershed characteristics. We recommend a peak coefficient of 0.62 as input to the Snyder unit hydrograph model for ungaged rural watersheds.

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PREFACE

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for
Kansas Department of Transportation

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Lag time is an essential input to the most common synthetic unit-hydrograph models. The lag time for an ungaged stream must be estimated from the physical characteristics of the stream and its watershed. In this study, a lag-time formula for small rural watersheds in Kansas was developed from gaging data. The database consisted of approximately a decade of 15-minute-interval rainfall and streamflow data for 19 rural watersheds with drainage areas from 2 km^2 to 36 km^2. We determined lag times for 200 significant events and estimated the average lag time for each watershed. We related the average lag time to the physical characteristics of the stream and watershed by stepwise multiple regression.

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The peak coefficients for the unit hydrographs of the gaged watersheds range from 0.46 to 0.77, with a mean of value of 0.62 and a standard deviation of 0.10. The peak coefficient is not correlated significantly with any of the watershed characteristics. We recommend a peak coefficient of 0.62 as input to the Snyder unit hydrograph model for ungaged rural watersheds.

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Chapter 1
Introduction

1.1 Time Parameters in Flood Hydrology

Time parameters such as lag time and time of concentration are essential inputs to common flood-discharge models. These measures of streamflow response time are related to physical features of the watershed such as drainage area, channel length and channel slope. An estimated watershed lag time is needed to develop a synthetic unit hydrograph (UH) by the methods of Snyder and the Natural Resources Conservation Service (formerly the Soil Conservation Service (SCS)). The calculation of design discharges by the rational method requires an estimation of the time of concentration.

Lag time (T_{lag}) has been defined in several different ways. In this study, lag time is defined as the time difference from the centroid of the net rainfall to the peak discharge at the watershed outlet. This definition is the one used in the Snyder and SCS synthetic UH models. Another common definition for lag time is the time difference from the centroid of the net rainfall to the centroid of the direct-runoff hydrograph. Other definitions are used infrequently. **Time of concentration (T_c)** is defined as the time required for a drop of water to flow to the watershed outlet from the most distant point in the watershed.

Direct determination of watershed lag time requires rainfall and streamflow data. However, most streams are ungaged. In practice, the lag time of ungaged stream must be estimated from physical characteristics of the stream and its watershed. Several formulas for watershed lag time have been published. Each formula has a limited range of applicability. None of these formulas appear to be appropriate for small rural watersheds in Kansas.

1.2 Unit Hydrograph Peak Coefficient

A common descriptor of the shape of a unit hydrograph is the peak coefficient, C_p. The peak coefficient is a dimensionless parameter defined by the formula

$$Q_p = \frac{C_p \cdot U \cdot A}{T_p} \qquad (1.1)$$

in which Q_p is the peak discharge, U is the unit depth of net rainfall, A is the drainage area and T_p is the time to peak. The time to peak is defined as the time from the start of the net rainfall to the peak discharge. The value of C_p is usually between 0.4 and 0.8. In the SCS synthetic UH method, C_p is assigned a constant value of 0.75. The Snyder synthetic UH method requires C_p as an input. The peak discharge on the synthetic UH is directly proportional to C_p. Fig. 1-1 shows the effect of the peak coefficient on the shape of the Snyder synthetic UH as implemented in the HEC-1 and HEC-HMS flood hydrograph programs of the U.S. Army Corps of Engineers.

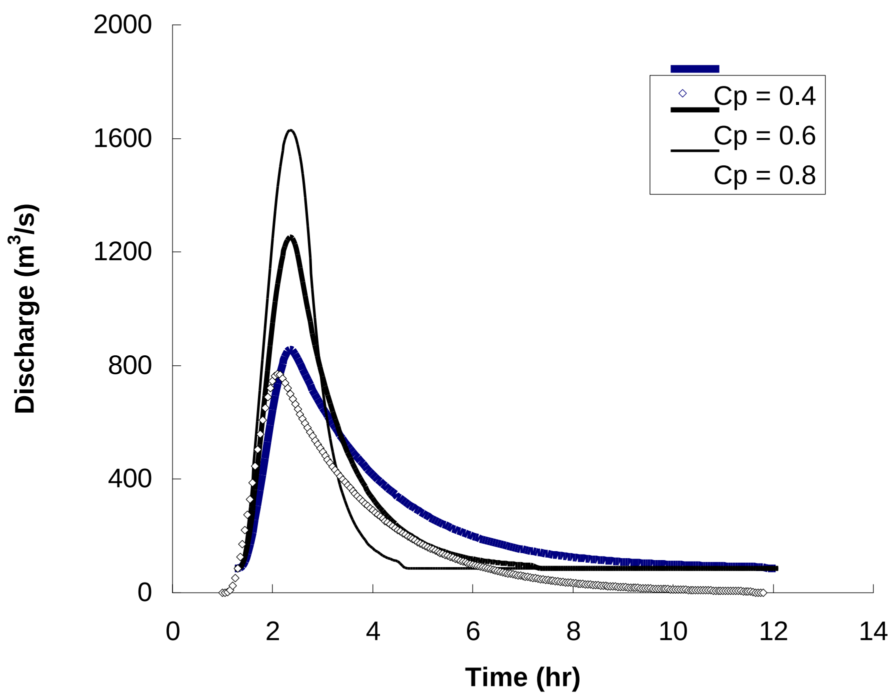


Fig. 1-1: Effect of C_p on the Shape of Snyder Synthetic UH

1.3 Objectives of Study

The primary objective of this research was to develop a simple and reliable formula for the lag times of small rural watersheds (50 km^2 or smaller) in Kansas based on local data. The second objective was to determine the average peak coefficient of the unit hydrographs of these watersheds.

Chapter 2
Review of Prior Studies

2.1 The Relationship between Lag Time and Time of Concentration

In flood hydrology, the lag time and time of concentration of a watershed are normally considered as constants, independent of the magnitude of the flood. Lag time is related to the travel time for the flood wave. Time of concentration is defined as the travel time for the water. The flood wave travels faster than the water. The relationship between the water speed and the wave speed depends mainly on the shape of the channel cross-section. The Manning friction formula is generally applied to flow in stream and to overland flow over rough surfaces. For overland flow and stream flow in wide shallow rectangular channels with Manning friction, the speed of a flood wave is 5/3 of the water speed, and the travel time for the flood wave is 3/5 of the travel time for the water. For streamflow in wide shallow parabolic channel, the travel time for the flood wave is 9/13 of the travel time for the water.

Watershed runoff includes both overland flow over irregular natural surfaces and stream flow in irregular natural channels. It is not possible to derive an exact mathematical relationship between lag time and time of concentration for a natural system. However, the time of concentration can be approximated as 5/3 of the lag time. This approximation is a common one in watershed hydrology. It is incorporated in the hydrologic methods of the Natural Resources Conservation Service (formerly the Soil Conservation Service, or SCS).

2.2 Formulas for Lag Time and Time of Concentration

Many different formulas have been developed for estimation of watershed time parameters. Each formula has certain limitations. In this section, several well-known formulas for lag time and time of concentration are reviewed.

Kirpich's formula is

$$T_c = 0.0663 \cdot \left(\frac{L}{\sqrt{S}}\right)^{0.77} \tag{2.1}$$

in which T_c is the time of concentration in hours, L is the length of main channel in kilometers, and S is the average slope of the main channel in m/m. The average channel slope is defined as the elevation difference between the upper end of the main channel (at the drainage divide) and the watershed outlet, divided by the length of the main channel.

Kirpich's formula was developed from data published by Ramser (1927). The data set contained the estimated times of concentration and physical characteristics for agricultural watersheds in Tennessee. The drainage areas ranged from 0.004 km^2 to 0.45 km^2 and the channel slopes ranged from 3% to 10%. Kirpich described these watersheds as follows:

> "These areas, all located on a farm in Tennessee, were characterized by well-defined divides and drainage channels, the topography being quite hilly, and typical of the steepest lands under cultivation in the vicinity. Owing to little or no protection against erosion, the top soil on the steeper slopes had been washed away (Kirpich, 1940)."

The reported times of concentration were as short as 1.5 min. These values were actually times to peak rather than times of concentration.

The Federal Aviation Administration formula is

$$T_c = 3.26 \cdot (11 - C) \cdot \frac{L^{0.5}}{S^{0.333}} \tag{2.2}$$

in which T_c is the time of concentration in hours, C is the runoff coefficient in the rational formula, L is the length of the overland flow in meters, and S is the surface slope in m/m. This formula was developed for airfield drainage. It is probably most valid for small watersheds where overland flow dominates (Federal Aviation Administration, 1970).

The SCS formula is

$$T_{lag} = 0.0057 \cdot \left(\frac{100}{CN} - 9\right)^{0.7} \cdot \frac{L^{0.8}}{\sqrt{S}} \tag{2.3}$$

in which T_{lag} is watershed lag time in hours, L is the length of the longest flow path in kilometers, S is the average watershed slope in m/m, and CN is the SCS runoff curve number. The runoff curve number depends on the soil type, surface cover and antecedent moisture conditions. This formula was developed from rainfall and streamflow data from agricultural watersheds (Soil Conservation Service, 1972).

Snyder's formula is

$$T_{lag} = C_t \cdot (L_{ca} \cdot L)^{0.3} \tag{2.4}$$

in which T_{lag} is watershed lag time in hours, L_{ca} is the distance along the main stream from the outlet to the point nearest the centroid of the watershed in kilometers, L is the total length of the main channel in kilometers, and C_t is a coefficient that varies geographically. For large watersheds in the Appalachian Highlands, Snyder found that the constant C_t varies from 1.4 to 1.7. Snyder reported that C_t is affected by slope, but did not specify a relationship (Snyder, 1938).

Carter's formula is

$$T_{lag} = 0.098 \cdot \left(\frac{L}{S}\right)^{0.6} \tag{2.5}$$

in which T_{lag} is watershed lag time in hours, L is the length of main channel in kilometers, and S is the average slope of the main channel. This formula was developed from data for urban watersheds in Washington, D.C. with storm sewers and natural channels. These watersheds all had drainage areas smaller than 51 km^2, channel lengths less than 17.7 km and average channel slopes less than 0.5%. Manning roughness coefficients for the channels ranged from 0.013 to 0.025 (Carter, 1961).

These formulas and other similar formulas have some common features. They all include multiple watershed characteristics. In several formulas, channel length and slope are grouped into a single independent variable, $L/S^{0.5}$. These formulas are of the form $T_c = K\,(L/S^{0.5})^c$ with different values for the coefficient, K, and exponent, c. All of these formulas have limited ranges of applicability. Most of these formulas were developed from data for watersheds of a particular type within a small region.

Maria Joao Correia De Simas (1997) attempted to develop a general formula for lag time. In her study, lag time was defined as the time from the centroid of the effective rainfall hyetograph to the centroid of the direct runoff hydrograph. She analyzed data from 168 watersheds from across the United States. Most of the watersheds were agricultural. Watershed characteristics such as average width, slope, and storage coefficient were used as independent variables. Both ungrouped log-transformed data and data grouped by regions and land use were used to calibrate the regression coefficients. The correlation coefficients of the multiple linear regression equations from this study are not very high (0.42 for ungrouped log-transformed data, 0.58 for the data grouped by regions and land use). However, this research clearly shows that the regression relationships are improved by grouping the watersheds by region and land use. In this research, the U.S. was divided into five regions: East, Midwest, Central, Southwest, and South. Because of more homogenous characteristics within small geographical regions, it is reasonable to expect higher correlation coefficients and better regression equations if smaller regions are studied.

2.3 Prior Studies of Unit Hydrograph Peak Coefficient

Typical values of C_p vary from region to region. Therefore C_p should be calibrated using local data. Many studies have been done to determine average values of C_p for specific regions and watershed types. Some reported average values of C_p are 0.6 for the Appalachian Highlands, 0.8 for central Texas and central Nebraska, and 0.9 for Southern California (Viessman, 1996). No prior studies are available for rural watersheds in Kansas.

Chapter 3

Lag Times and Peak Coefficients for Gaged Watersheds

3.1 Climate and Hydrology of Kansas

The climatic and hydrology of Kansas vary greatly with geographic location. Normal annual precipitation ranges from 1000 mm in the northeast corner to 400 mm in the west. Seventy-five percent of annual precipitation falls between April and September. Average annual lake evaporation ranges from 1110 mm in the northeast to 1700 mm in the southwest. In the western half of the state, annual lake evaporation is 200% to 500% of annual precipitation (NOAA, 1982). The geographic variation in average annual runoff is extreme. Average annual runoff ranges from 250 mm in the southeast to 2.5 mm in the west, a 100-fold variation (Kansas Water Resources Board, 1967).

Two main types of floods may be distinguished. One type is localized flash flooding on small watersheds. Such floods are common and can occur in any part of the state in any season of the year. Floods of this type are caused by thunderstorms that produce intense rains of short duration and cover relatively small areas. The second type of flooding occurs less often on the large rivers. These floods, which can produce widespread damage over prolonged periods, are caused by storms that last for several days and cover thousands of square kilometers. Both types of floods occur most frequently in May, June and July.

3.2 Selection of Gaged Watersheds

The focus of this study is small rural watersheds in Kansas. Twenty-one watersheds gaged by the USGS were selected for study. These watersheds met three criteria: (1) rural land use, (2) drainage area smaller than 50 km^2, and (3) 15-minute recording interval for streamflow data and rainfall data. Fig. 3-1 shows the locations of the 21 gaging stations. Fifteen stations are located in the eastern half of the state, and six are located in the western half. These stations were operated by the USGS during the period of 1965-1982 to gather data for the calibration of rainfall-runoff models. Table 3-1 shows the periods of record for the individual gages. Each station had a recording rain gage at the same location as the stream gage.

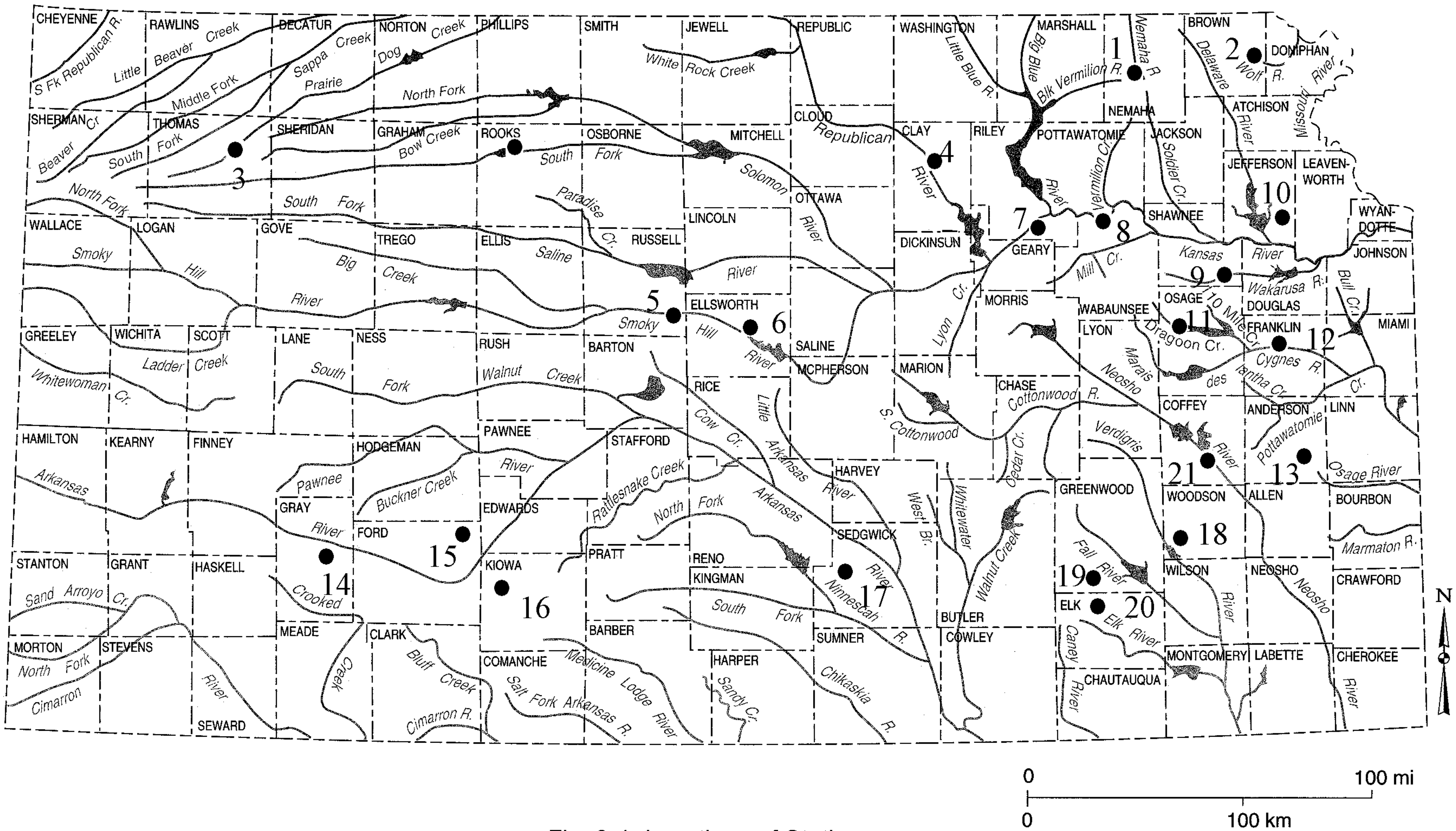


Fig. 3-1: Locations of Stations

Table 3-1: Periods of Record for Selected Stations

Map # (1)	USGS Station # (2)	Station Name (3)	CDA (km2) (4)	Periods of Record (5)
1	6813700	Tennessee Creek Trib. near Seneca	2.33	06/05/67-07/02/76
2	6815700	Buttermilk Creek near Willis	9.69	07/27/65-0704/74
3	6847600	Prairie Dog Creek Trib. near Oskaloosa	19.50	05/09/71-06/27/82
4	6856800	Moll Creek near Green	9.32	09/20/65-09/26/73
5	6864300	Smoky Hill R. Trib. at Dorrance	13.96	08/13/75-07/19/82
6	6864700	Spring Creek near Kanopolis	25.49	04/15/76-05/31/82
7	6879650	Kings Creek near Manhattan	11.37	10/01/88-09/31/96
8	6887600	Kansas River Trib. near Wamego	2.15	06/11/67-05/6/76
9	6888900	Blacksmith Trib. near Valencia	3.39	05/31/67-06/22/75
10	6890700	Slough Creek Trib. near Oskaloosa	2.15	06/05/67-05/30/76
11	6912300	Dragoon Creek Trib. near Lyndon	9.74	06/20/67-05/28/75
12	6913600	Rock Creek near Ottawa	26.42	08/18/66-09/03/74
13	6916700	Middle Creek near Kincaid	5.23	08/21/66-09/02/74
14	7139700	Arkansas R. Trib. near Dodge City	22.43	07/07/77-08/05/82
15	7140300	Whitewoman Creek Trib. near Bellefont	36.26	08/05/77-09/07/81
16	7142100	Rattlesnake Creek Trib. near Mullinville	26.68	05/22/77-08/29/81
17	7145300	Clear Creek near Garden Plain	13.03	05/20/77-09/14/82
18	7166200	Sandy Creek near Yates Center	17.61	06/24/67-06/17/75
19	7169200	Salt Creek near Severy	19.66	06/27/67-07/05/76
20	7169700	Snake Creek near Howard	4.77	07/05/67-07/03/76
21	7182520	Rock Creek at Burlington	21.42	06/12/67-06/29/76

3.3 Selection of Rainfall-Runoff Events

Watershed lag times tend to be fairly consistent for floods with return periods of two years or greater. All floods with estimated return periods of two years or greater were identified for further study. Some smaller floods were also studied.

In this study, a rainfall event is considered as a single storm if its point-rainfall record contained no break period of zero rainfall longer than twice the estimated lag time of the watershed. The storms selected for this study include single-period and multi-period storms. Multi-period storms are storms that produce two or more periods of heavy rainfall, separated by periods of little or no rainfall. An example of a single-period event is shown in Fig. 3-2.

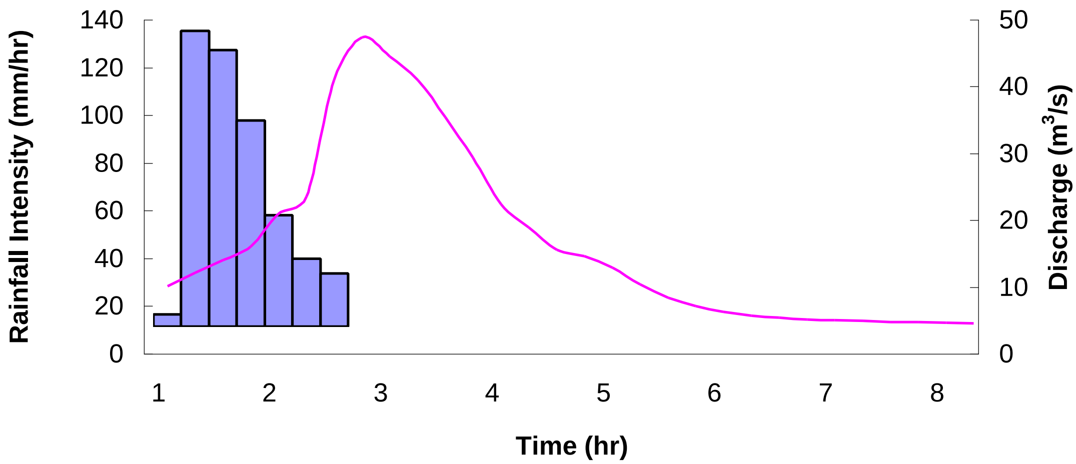


Fig. 3-2: Example of a Selected Event

Initially, 200 significant storms were identified. Further criteria were used to filter out events with unreasonable-looking records. If the record indicated that the runoff began before the rainfall started or after the rainfall ended, the event was discarded.

3. 4 Computation of Lag Times

The parameter calibration feature in the HEC-1 flood hydrograph program (U. S. Army Corps of Engineer, September, 1990) was used to determine the lag times for the individual events. Each watershed was modeled as a single basin. The rainfall recorded at the watershed outlet was applied to the entire watershed.

3.4.1 Computation of Net Rainfall Hyetograph

The computation of lag times from rainfall and streamflow data requires the separation of base flow and the computation of net rainfall. Base flow is the contribution of shallow ground water to streamflow. In large watersheds, base flow may be a significant fraction of streamflow. For small streams in Kansas, base flow is a very small percentage of the total streamflow during floods. Most of the events selected for this study had no base flow. For those events with non-zero streamflow at the start of rainfall, we assumed a constant base flow equal to the initial streamflow. The base flow was subtracted from the total storm hydrograph to obtain the direct runoff hydrograph.

The “initial and uniform” loss model was used to compute the net rainfall. In the “initial and uniform” loss model, all rainfall is lost until the specified initial loss is satisfied. After the initial loss is satisfied, rainfall is lost at a specified constant rate. The initial loss and the uniform loss rate for each event were determined by calibration within HEC-1.

3.4.2 Unit Hydrograph Model

In HEC-1, a synthetic unit hydrograph can be generated by several different models, including the Snyder and SCS models. The Snyder synthetic UH in HEC-1 has two parameters: the watershed lag time and the peak coefficient. The SCS synthetic UH has only one parameter: the watershed lag time. The SCS synthetic UH has a constant peak coefficient of 0.75. The values of the synthetic UH parameters can be determined by calibration module within HEC-1.

Initially, the Snyder and SCS synthetic UH models were both tested, and the results were compared. The comparisons were based on the relative error of peak discharge, DQ_p, and on the relative error of time to peak, DT_p. These two variables are defined by Eq. 3.1 and Eq. 3.2:

$$DQ_p = \frac{Q_{ob} - Q_{comp}}{Q_{ob}} \cdot 100\% \tag{3.1}$$

$$DT_p = \frac{T_{ob} - T_{comp}}{T_{ob}} \cdot 100\% \tag{3.2}$$

in which Q_{ob} is the observed peak discharge, Q_{comp} is the computed peak discharge, DQ_p is the relative error in the computed peak discharge, T_{ob} is the observed time to peak, T_{comp} is the computed time to peak, and DT_p is the relative error in the computed time to peak.

Table 3-2 shows the results for eight events at station 6815700. These results indicate that both the Snyder and the SCS UH models can be used to obtain satisfactory estimates of lag times. The two models yield similar lag times. The relative errors in the times to peak are small. However, the average relative error in peak discharge is 13% higher for the SCS UH model than for the Snyder UH model. The average peak coefficient for the calibrated Snyder unit hydrographs is 0.68, 11% lower than the constant peak coefficient of 0.75 in the SCS unit hydrograph. These results indicate that the SCS UH model tends to overestimate peak discharges on small rural watersheds. The results also show no apparent relationship between peak coefficient and lag time. Time-to-peak and peak discharge are the two main issues of the evaluation of synthetic UH models. According these two criteria, it appears that recorded hydrograph can be matched better with the Snyder UH than with the SCS UH model. For this reason, the Snyder UH model was selected for the calibration of lag times.

Table 3-2: Comparison of Calibration Results Using Snyder and SCS UH Models

	Snyder				SCS UH		
Events (1)	**DQ_p (%) (2)**	**DT_p (%) (3)**	**T_{lag} (4)**	**C_p (5)**	**DQ_p (%) (6)**	**DT_p (%) (7)**	**T_{lag} (8)**
1	0.1	0.0	0.94	0.77	8.3	3.8	0.61
2	-1.1	-5.7	0.68	0.77	8.4	0.0	0.50
3	10.2	0.0	1.29	0.61	30.6	0.0	1.38
4	2.2	-7.0	1.27	0.5	38.0	-2.9	1.30
5	32.0	0.0	1.67	0.76	36.0	0.0	1.30
6	-5.6	5.0	1.71	0.62	10.0	-3.6	1.67
7	8.0	-5.7	1.33	0.72	12.6	-5.7	1.26
8	11.0	0.0	1.30	0.71	22.0	0.0	1.30
Average	7.1	-1.7	1.27	0.68	20.7	-1.1	1.16

3.4.3 Parameter Estimation in HEC-1

HEC-1 uses a numerical index to measure the closeness of fit of the computed and observed hydrographs. The objective function that is minimized by optimization routine is a discharge-weighted root-mean-square error. This objective function, STDER, is defined as

$$STDER = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (Q_{obsi} - Q_{compi})^2 \cdot WT_i} \tag{3.3}$$

in which Q_{obsi} and Q_{compi} are the observed and computed discharges at time index i, WT_i is the weighting factor for time index i, and n is the number of ordinate on the observed hydrograph. The weighting factor, WT_i, equals $(Q_{obsi} + Q_{compi}) / 2 * Q_{ave}$, in which Q_{ave} is the average observed discharge. This objective function provides an index of how closely the observed hydrograph is replicated. It is weighted to emphasize the closeness of the fit at the high flows. An improvement in the fit at the highest flows yields the greatest reduction in the objective function (U.S Army Corps of Engineers, 1990). This emphasis on high flows is appropriate for flood hydrograph analysis.

HEC-1 uses a univariate gradient search procedure to determine the optimal parameter estimates. This search procedure minimizes the partial derivatives of the objective function with respect to the unknown parameters. A single parameter is varied in each iteration. The derivatives are estimated numerically, and Newton’s technique is used to improve parameter estimates. The optimization does not guarantee a “global optimum” solution of the objective function. Different initial values can result in different optimal values.

3.5 Lag Times for Individual Events

We used the HEC-1 parameter calibration feature to find the values of four parameters for each event. These four parameters are the initial loss and uniform loss rate in the loss model and the lag time and peak coefficient in the Snyder UH model. An example HEC-1 input file is shown in Table 3-3. We made two calibration runs for each event. The optimal results from the first run were used as the initial values for the second run. An appendix shows the final results of the calibrations. A calibration was considered successful if the relative errors in the peak discharge and the time-to-peak (DQ_p and DT_p) were both smaller than 20 percent. Successful calibrations were achieved for 124 events from the records of 19 stations. Station 6864300 and

7140300 were excluded from further analysis due to the large errors in the calibrations. Fig. 3-3 shows calibrated lag time versus peak discharge for the events with satisfactory calibrations at each of these stations. At most stations, the lag times for the different events are fairly consistent. Some of the graphs exhibit a tendency toward slightly larger lag time for the smaller events.

Table 3-3: Example of HEC-1 Input File

```
*FREE
ID  ESTIMATION OF LAG TIME
ID  ROCK C AT BURLINGTON, KS
ID  7182520
IT  3  20JUN67  2215  300
IN   15
OU
* ******
KK  SUB1
BA  8.27
BF  43
PB  0
PI  .02    .04    .06    .08    .02    .46
PI  .18    .70    .42    .34    .22    .02
PI  .02    .00    .00    .00    .00    .00
PI  .00    .00    .06    .00    .52    .40
PI  .06    .16    .06    .02
QO    43.00      43.00      43.00      43.00      43.00      43.00
QO    43.00      63.00     131.80     226.40     301.60     348.00
QO   379.20     400.80     420.00     444.80     488.00     566.40
QO   710.00    1015.00    1355.00    1694.00    2076.00    2360.00
QO  2520.00    2590.00    2570.00    2480.00    2390.00     287.00
QO  2196.00    2108.00    2020.00    1948.00    1876.00    1812.00
QO  1756.00    1708.00    1664.00    1622.00    1568.00     502.00
QO  1412.00    1325.00    1220.00    1100.00     970.00     844.00
QO   731.00     630.40     577.60     525.50     481.00     447.20
QO   419.20     391.20     364.00     339.20     198.30     182.20
QO   166.10     150.70     135.30     120.60     107.30      97.40
QO    89.00      82.00      77.00      72.50      69.00      65.60
QO    62.50      60.00      57.50      55.00      52.50      50.50
QO    48.50      46.50      44.50
LU     -1         -1          0
US     -1         -1
ZZ
```

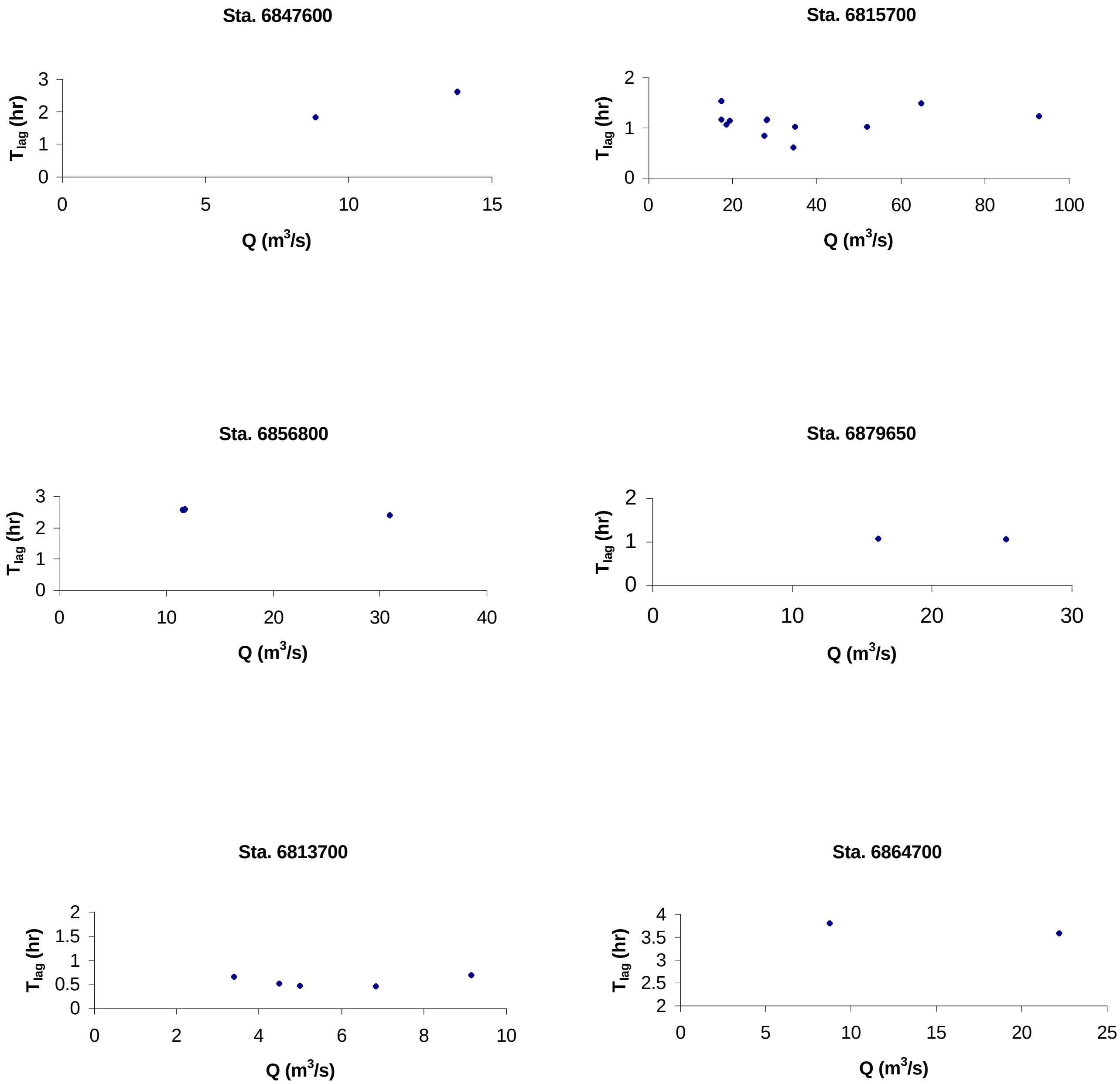


Fig. 3-3: Lag Times vs. Peak Discharges

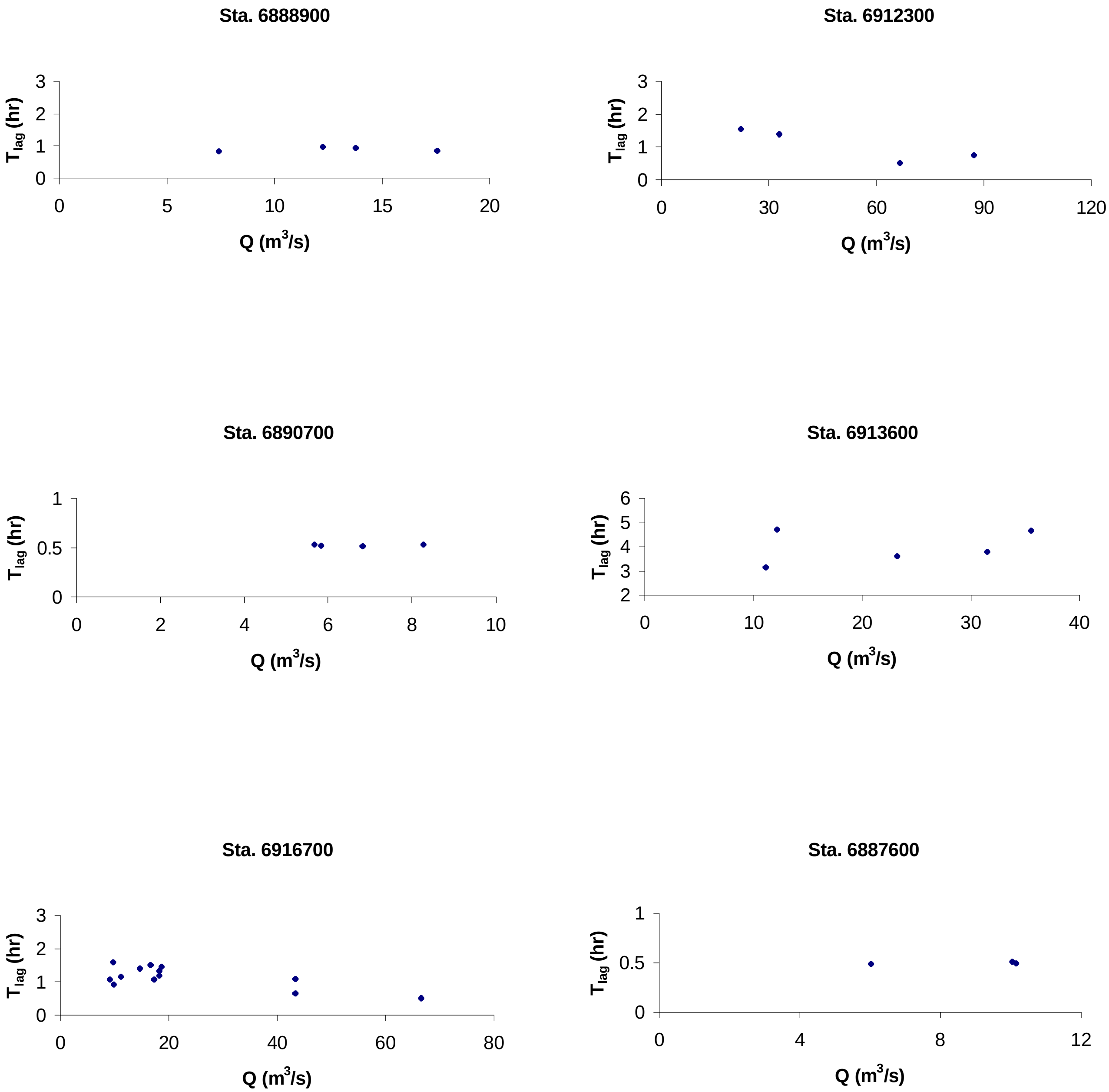
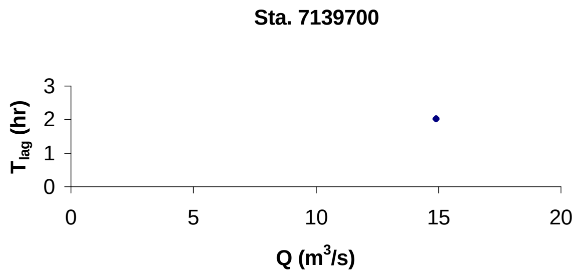
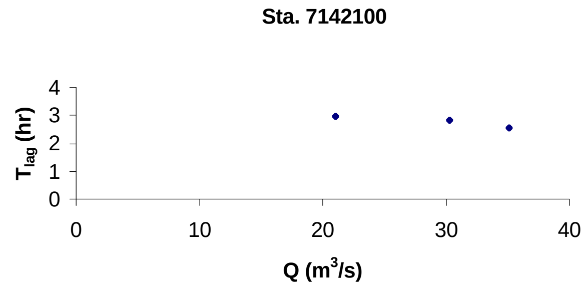
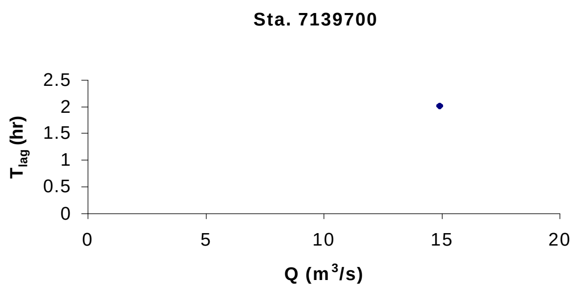
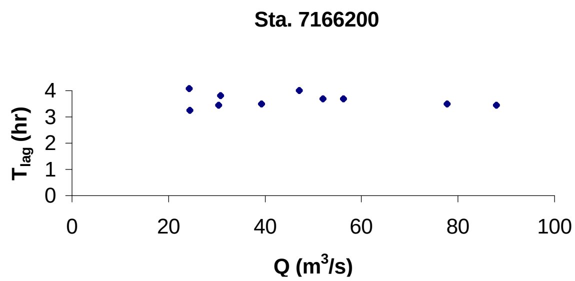


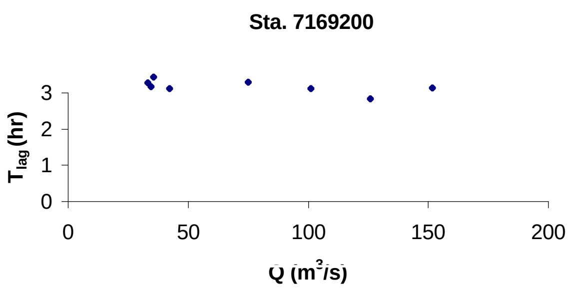
Fig. 3-3: Lag Times vs. Peak Discharges (continued)











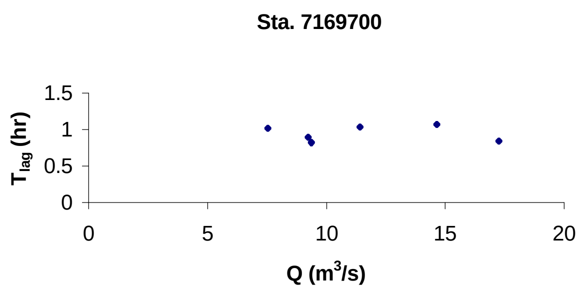


Fig. 3-3: Lag Times vs. Peak Discharges (continued)

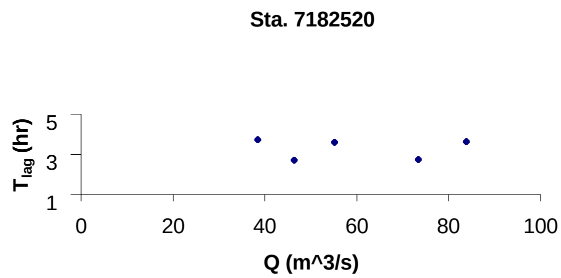


Fig. 3-3 Lag Times vs. Peak Discharges (continued)

3.6 Average Lag Times for Gaged Watersheds

The lag times from the individual events were averaged to obtain a single lag time for each watershed. The average peak coefficient for each watershed was also computed. Table 3-4 shows the average lag times and peak coefficients for the 19 watersheds. An appendix shows the lag times and peak coefficients for the individual events. Lag times that differed greatly from the median value for the watershed were not used to compute the average lag time. Most of the excluded events were minor events.

Table 3-4: Average Lag Times and Peak Coefficients for the Gaged Watersheds

Map # (1)	Station # (2)	T_{lag} (hr) (3)	C_p (4)
1	6813700	0.56	0.50
2	6815700	1.15	0.66
3	6847600	2.23	0.58
4	6856800	2.52	0.55
5	6864700	3.69	0.66
6	6879650	1.07	0.76
7	6887600	0.50	0.61
8	6888900	0.89	0.66
9	6890700	0.52	0.55
10	6912300	1.05	0.77
11	6913600	3.22	0.52
12	6916700	1.15	0.71
13	7139700	2.02	0.59
14	7142100	2.77	0.46
15	7145300	1.78	0.47
16	7166200	2.59	0.61
17	7169200	1.93	0.77
18	7169700	0.95	0.56
19	7182520	3.29	0.77
		Average C_p:	**0.62**

Chapter 4

Regression Analysis of Lag Times and Peak Coefficients

4.1 Selection of Independent Variables

Common sense indicates that lag time must be related to physical and climatic characteristics of the watershed. The unit hydrograph peak coefficient could also be dependent on certain watershed characteristics. Regression analyses were performed to quantity these relationships. Watersheds characteristics considered as independent variables in the regression analysis are defined as follows:

1. Contributing drainage area (CDA).
2. Channel length (L): the total length of the main channel, extended to the drainage divide.
3. Average channel slope (S): the elevation difference between two points on the channel, located 10% and 85% of the channel length (L) upstream of the gage, divided by the length of channel between these two points (0.75 L).
4. Watershed shape factor (Sh): the dimensionless ratio CDA/L^2.
5. Soil permeability (SP): a generalized estimate of the permeability of soil within the watershed, obtained from a statewide map (USGS, 1987).
6. Two-year, 24-hour rainfall (I2): the 24-hour rainfall depth with a 2-year return period.
7. Latitude (Lat): the latitude at the gage.

Table 4-1 shows the values of these characteristics for the 19 stations. These values were provided by the USGS. To examine the relationship among these independent variables and the two dependent variables, correlation analyses were performed. The correlation matrix is shown in Table 4-2.

Lag time is strongly correlated with channel length (r = 0.89), contributing drainage area (r = 0.84), watershed shape factor (r = 0.79), and channel slope (r = -0.75). Lag time is only weakly correlated with soil permeability (r = 0.24) and the 2-yr, 24-hour rainfall (r = -0.24). All of these correlation coefficients are significantly different from zero at the 95% significance level. The correlation analyses further show the relationship between peak coefficient and lag time is weak.

Table 4-1: Physical Characteristics of Gaged Watersheds

Map # (1)	USGS Station # (2)	CDA (km^2) (3)	S (m/m) (4)	Sh (km^2/km^2) (5)	Lat (degee) (6)	I2 (mm) (7)	SP (mm/hr) (8)	L (km) (9)
1	6813700	2.33	0.01176	3.44	39.812	83.82	2.54	2.83
2	6815700	9.69	0.01273	3.27	39.754	86.36	22.86	5.63
3	6847600	19.50	0.00316	3.45	39.391	58.42	33.02	8.20
4	6856800	9.32	0.00386	6.66	39.380	81.28	5.08	7.88
5	6864700	25.49	0.00337	8.80	38.739	76.20	17.78	14.98
6	6879650	11.37	0.01448	2.23	39.100	86.61	17.78	5.04
7	6887600	2.15	0.01826	4.08	39.174	86.36	17.78	2.96
8	6888900	3.39	0.01248	2.33	39.022	88.90	17.78	2.81
9	6890700	2.15	0.01125	2.46	39.201	88.90	2.54	2.30
10	6912300	9.74	0.00684	2.20	38.692	91.44	17.78	4.63
11	6913600	26.42	0.00227	5.79	38.554	91.44	17.78	12.37
12	6916700	5.23	0.00686	2.28	38.056	96.52	2.54	3.45
13	7139700	22.43	0.00265	8.64	37.714	66.04	22.86	13.92
14	7142100	26.68	0.00248	7.26	37.586	71.12	25.40	13.92
15	7145300	13.03	0.00290	5.97	37.663	86.36	17.78	8.82
16	7166200	17.61	0.00366	5.56	37.846	93.98	2.54	9.90
17	7169200	19.66	0.00415	2.43	37.620	96.52	17.78	6.91
18	7169700	4.77	0.00727	3.13	37.541	96.52	17.78	3.86
19	7182520	21.42	0.00158	7.26	38.196	93.98	17.78	12.47

Table 4-2: Correlation Matrix for the Independent Variables and Dependent Variables

	CDA	S	Sh	Lat	I2	SP	L	C_p	T_{lag}
CDA	1								
S	-0.77	1							
Sh	0.69	-0.62	1						
Lat	-0.44	0.59	-0.31	1					
I2	-0.39	0.22	-0.44	-0.20	1				
SP	0.49	-0.17	0.17	-0.10	-0.54	1			
L	0.94	-0.77	0.89	-0.44	-0.43	0.38	1		
C_p	0.02	0.15	0.33	0.02	0.38	0.05	0.16	1	
T_{lag}	0.84	-0.75	0.79	-0.29	-0.24	0.24	0.89	0.05	1

Note: Tabulated values are the correlation coefficients, r, for the base-10 logarithms of the values.

Regression analysis is valid only if the independent variables are not strongly correlated. Violation of this rule generally results in unstable regression coefficients, and it becomes difficult to evaluate the relative importance of the interrelated variables. The correlation matrix was used to identify the combinations of variables that might cause problems in the regression analysis. Contributing drainage area is strongly correlated with channel length (r = 0.94) and channel slope (r = -0.77). Channel length is strongly correlated with watershed shape factor (r = 0.89) and channel slope (r = 0.77). The highest correlation coefficient for peak coefficient is 0.38 (with I2). The low correlation coefficients indicate that the peak coefficient is not strongly correlated with any of these independent variables.

Logically, channel length and channel slope should both be important explanatory variables for lag time. The time required for a flood wave to pass through a channel is directly proportional to the channel length and inversely proportional to the wave speed. Hydraulic formulas indicate that the speed of a flood wave is proportional to the square root of the channel slope. Therefore, the travel time for a flood wave in a channel with no lateral inflow is directly proportional to $L/S^{0.5}$. Although a natural watershed is a much more complex system than a simple channel, its lag time should also be closely related to the quantity $L/S^{0.5}$. Therefore, this quantity was considered as a single independent variable in the regression analysis. The correlation coefficient between lag time and $L/S^{0.5}$ is 0.93.

4.2 Multiple Regression Analysis of Lag Times

Stepwise multiple linear regression was performed using the SPSS statistics software. The regression model used in this analysis is the power function

$$T_{lag} = a_0 \cdot x_1^{a_1} \cdot x_2^{a_2} \cdot x_3^{a_3} \ldots \quad (4.1)$$

in which x_1, x_2, x_3… are independent variables, a_0 is the regression constant, and a_1, a_2, a_3… are regression coefficients. Logarithmic transformation of Eq. 4.1 results in an equation that is linear with respect to the logarithms of the variables.

$$\log(T_{lag}) = \log(a_0) + a_1 \cdot \log(x_1) + a_2 \cdot \log(x_2) + a_3 \cdot \log(x_3) \cdots \quad (4.2)$$

Eq. 4.2 was fitted to the data by performing a stepwise multiple linear regression analysis on the logarithms of the data. Initially, A, S, Sh, L, I2, SP were all included as possible independent variables. The resulting best-fit regression equation was

$$T_{lag} = 0.087 \cdot \frac{A^{0.43}}{S^{0.36}} \quad (4.3)$$

Eq. 4.3 has a standard error of 0.087 and a coefficient of determination (r^2) of 0.91. The stepwise regression analysis was repeated with $L/S^{0.5}$ as an additional independent variable. The resulting best-fit equation was

$$T_{lag} = 0.086 \cdot \left(\frac{L}{\sqrt{S}}\right)^{0.64} \quad (4.4)$$

Eq. 4.4 has a standard error of 0.088 and a coefficient of determination (r^2) of 0.91.

A third regression analysis was performed with channel length and channel slope as the independent variables. The resulting equation was

$$T_{lag} = 0.102 \cdot \frac{L^{0.69}}{S^{0.27}} \quad (4.5)$$

The standard error of estimate is 0.090 and the coefficient of determination (r^2) is 0.89.

The regression results show that the length, area and slope are the most important independent variables. The addition of other variables does not increase the value of r^2 significantly. All three regression equations are statistically significant (Sig. F<0.05). The correlation coefficients and standard errors of estimate are almost the same for the three regression equations. However, because channel slope is highly correlated with channel length and contributing drainage area, the coefficients in Eq. 4.3 and Eq. 4.5 are uncertain. Table 4-3 compares the standard errors of the coefficients in the three equations. The coefficients in Eq. 4.3 and 4.5 have much higher standard errors than the coefficients in Eq. 4.4. The single independent variable $L/S^{0.5}$ yields a more reliable regression equation. The recommended regression equation for lag time is Eq. 4.4. In percentage term, its standard error of estimate is approximately 24%.

Table 4-3: Comparison of Standard Errors of Regression Coefficients

Equation **(1)**	**Regression Coefficients** **(2)**	**Value** **(3)**	**Std. Error** **(4)**	**Std. Error (% of value)** **(5)**
Eq. 4.3	constant	-1.060	0.187	17.6
	log (A)	0.426	0.093	21.8
	log (S)	-0.358	0.112	31.3
Eq. 4.4	constant	-1.058	0.098	9.3
	$\log (L/S)^{0.5}$	0.636	0.049	7.7
Eq. 4.5	constant	-0.990	0.208	21.0
	log (L)	0.694	0.163	23.5
	log (S)	-0.268	0.137	51.1

The bias of Eq. 4.4 was analyzed statistically. Ideally, a regression model should be unbiased. The mean residual can be used as an estimate of bias. If the mean residual is significantly different from zero, it reflects a bias in the model. The residuals should be approximately normally distributed with a mean of zero. The t statistical test is used to test the significance of the bias. The value of the t-test statistic is 0.93. For 18 degrees of freedom and a

2 percent level of significance, the critical value of t is 2.55. Therefore, the null hypothesis of unbiasedness cannot be rejected, which implies that the model is unbiased.

A total F test can be used to determine whether or not the dependent variable is significantly related to the independent variables that have been included in the equation. According the result of regression analysis, the value of the total F test statistic is 168. With 98% confidence, this value is larger than the critical value of 8.40. Therefore, the hypothesis that the dependent variables are significantly related to the independent variable can be accepted with 98% confidence.

From the results of the regression analysis, t-test statistics values for the coefficient and exponent in Eq. 4.4 are -10.8 and 12.9, respectively. Both of these values are larger than the critical value of $t_{1-0.01}(18)$, which is 2.55, so the relationship between T_{lag} and $L/S^{0.5}$ is significant with 98% confidence.

Fig. 4-1 compares the lag times from Eq. 4.4 with the lag times from the gaging data.

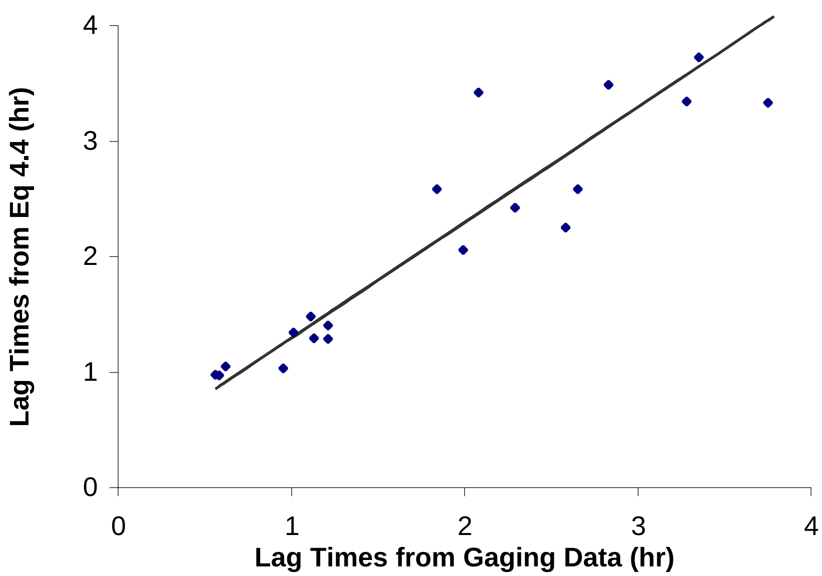


Fig. 4-1: Comparison of Lag Times from Regression Equation and Gaging Data

As a further test of the validity of the regression model, split-sample testing was performed. A new regression equation was developed from the data number 1 through 16 in Table 3-4 and Table 4-1. The resulting equation is

$$T_{lag} = 0.088 \cdot (\frac{L}{\sqrt{S}})^{0.64} \tag{4.6}$$

This equation is almost the same as Eq. 4.4. When Eq. 4.6 is applied to the remaining data, the highest prediction error is 11.3% and the average prediction error is 6.1%. This test indicates the regression equation yields acceptable estimates of lag times for watersheds not considered in the development of the equation. Therefore the regression equation Eq. 4.4, which was developed with all of the data, can be accepted.

4.3 Comparison of New Lag-Time Formula and Kirpich's Formula

Kirpich's formula for time of concentration (Eq. 2.1) has been widely used in Kansas for many years. Multiplying Eq. 2.1 by 0.6 yields a corresponding equation for lag time:

$$T_{lag} = 0.0398 \cdot (\frac{L}{\sqrt{S}})^{0.77} \tag{4.7}$$

Fig. 4-2 compares the new lag-time formula Eq. 4.4 and the Kirpich's lag-time formula Eq. 4.7. Kirpich's formula underestimates the lag times of the gaged watersheds by 16% on average. This tendency toward underestimation is strongest for watersheds with very short lag times. The exponent on the independent variable, $L/S^{0.5}$, in Eq. 4.7 appears to be too large. For large watersheds ($L/S^{0.5} > 300$), Kirpich's formula could tend to overestimate lag times. It is important to note that the watersheds in Kirpich's study had times of concentration that ranged from 1.5 to 17 minutes. The corresponding lag times were 0.9 to 10 minutes. The largest value of $L/S^{0.5}$ in Kirpich's study was 7.2 km. Therefore, the Kirpich's formula should not be applied to watersheds with values of $L/S^{0.5}$ much larger than 7.2 km. All of the gaged watersheds in our study are actually outside the range of applicability of the Kirpich's formula. Eq. 4.4 was developed from rural watersheds with drainage areas smaller than 50 km^2. It should provide reasonable estimates of lag times for rural watersheds as large as 50 km^2 with values of $L/S^{0.5}$ less than 320 km.

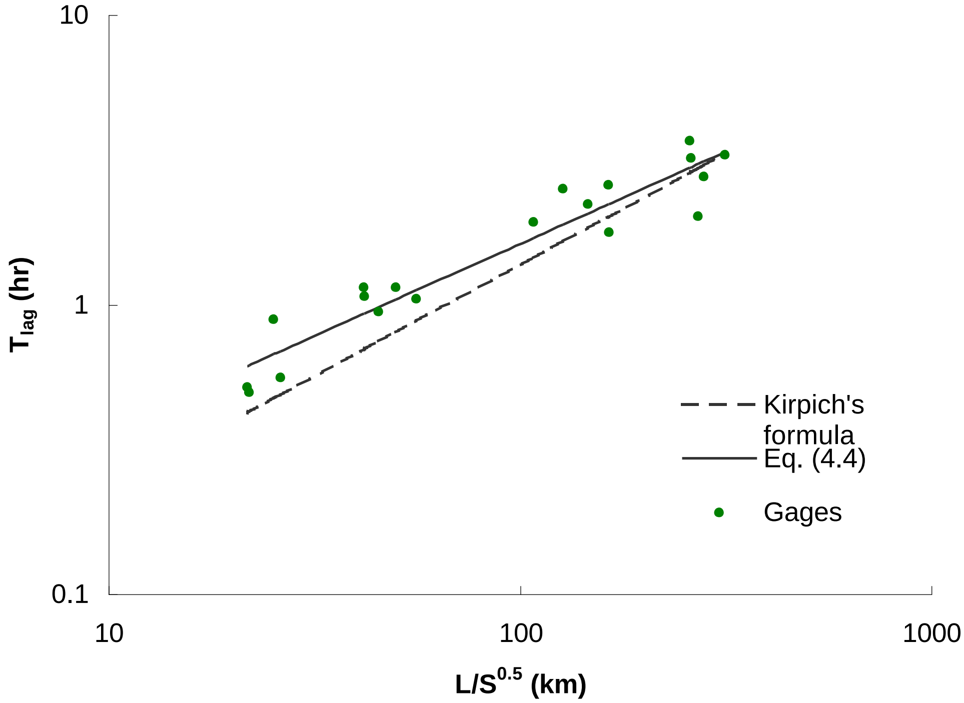


Fig. 4-2: Comparison of Lag-Time Formulas

4.4 Analysis of Peak Coefficients

The correlation analysis shows that C_p is not strongly correlated with any of the watershed characteristics. The averaged C_p values for the gaged watersheds range from 0.46 to 0.77. Fig. 4-3 shows the frequency distribution of these values. These values have a mean of 0.62 and a standard deviation of 0.13. Therefore, we recommend using C_p = 0.62 in the Snyder UH model for ungaged watersheds. This recommendation applies to rural watersheds in Kansas with drainage areas up to 50 km^2.

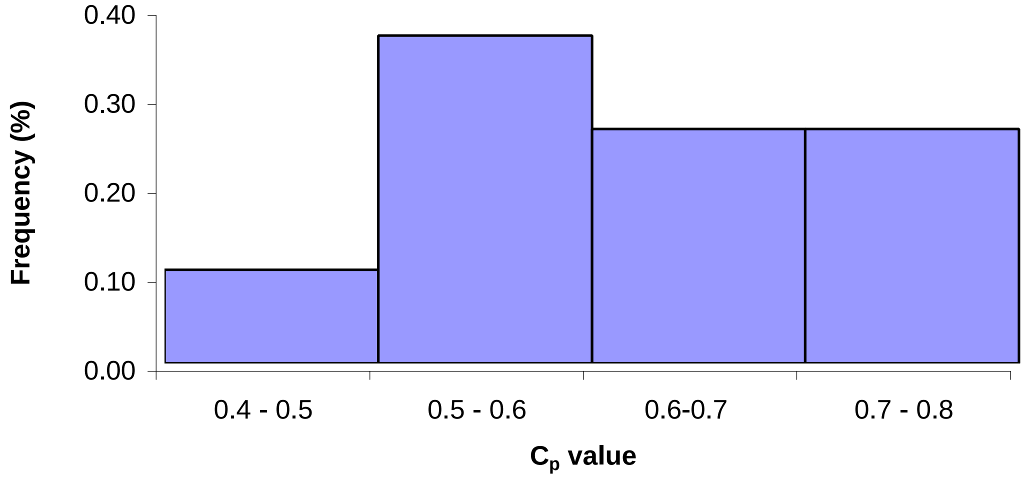


Fig. 4-3: Frequency Distribution of C_p for Gaged Watersheds

4.4 Analysis of Peak Coefficients

The correlation analysis shows C_p is not strongly correlated with any of the watershed characteristics. The averaged C_p values for the gaged watersheds range from 0.46 to 0.77. Fig. 4-3 shows the frequency distribution of these values. These values have a mean of 0.62 and standard deviation of 0.13. Therefore, we recommend using C_p = 0.62 in the Snyder UH model for the ungaged watersheds. This recommendation applies to rural watersheds in Kansas with drainage areas up to 50 km^2.

Chapter 5

Conclusions

Watershed lag times and unit hydrograph peak coefficients can be estimated from rainfall and streamflow data for individual events. Larger events tend to have fairly consistent lag times and peak coefficients. Average lag times can be related to watershed characteristics by regression analysis. For small rural watersheds in Kansas, the two most significant explanatory variables are the length and average slope of the stream. However, length and slope are highly correlated. Inclusion of length and slope as separate independent variables leads to unstable regression coefficients. Combining these two variables into a single independent variable, $L/S^{0.5}$, yields a satisfactory regression formula with stable coefficients.

The recommended formula for the lag times of small rural watersheds in Kansas is

$$T_{lag} = 0.086 \cdot \left(\frac{L}{\sqrt{S}}\right)^{0.64}$$

for T_{lag} in hours, L in km and S in m/m. The variable L is the total length of the main channel, extended to the drainage divide. The variable S is the elevation difference between two points on the channel, located 10% and 85% of the channel length from the outlet, divided by the length of channel between the two points (0.75 L). This formula has a standard error of estimate of approximately 24%. It is applicable to watersheds with drainage areas up to 50 km^2.

The peak coefficients for the unit hydrographs of the gaged watersheds range from 0.46 to 0.77, with a mean of value of 0.62 and a standard deviation of 0.10. The peak coefficient is not correlated significantly with any of the watershed characteristics. We recommend a peak coefficient of 0.62 as input to the Snyder unit hydrograph model for ungaged rural watersheds.

References

1. Bell, F. C., and Kar, S. O. (1969). "Characteristic Response Times in Design Flood Estimation." *Journal of Hydrology,* Vol. 8, No 2. pp. 173-196.
2. Carter, R. W. (1961). "Magnitude and Frequency of Floods in Suburban Areas," *U.S. Geological Survey Prof. Paper 424-B,* pp. B9-B11.
3. Federal Aviation Administration (1970). " Circular on Airport Drainage," *Report A/C 050-5320-5B*, Washington, D.C..
4. Hoggan, D. (1996). *Computer-Assisted Floodplain Hydrology and Hydraulics*, pp. 124-129.
5. Kansas Water Resources Board (1967). *Kansas Water Atlas*.
6. Kirpich, P. Z. (1940). "Time of Concentration of Small Agricultural Watersheds," *Civil Engineering*, Vol. 10, No. 6. pp. 362.
7. Maidment, David R. (1992). *Handbook of Hydrology*, pp. 9.35-9.36.
8. McCuen, Richard H. (1989). *Hydrologic Analysis and Design*, pp. 115-123.
9. McEnroe, B.M. (1992). "Evaluation and Updating of Hydrologic Analysis Procedures Used by KDOT," *Report No. K-TRAN: KU-92-1, Vol. I*, Kansas Department of Transportation.
10. National Oceanic and Atmospheric Administration (1982). *Evaporation Atlas for the Contiguous 48 United States*.
11. Ramser, C. E. (1927). "Runoff from Small Agricultural Areas," *Journal of Agricultural Researc*h, Vol. 34, No. 9.
12. Simas, Maria Joao Correia De. (1997*). Lag Time Characteristics in Small Watersheds in The United States* (Ph.D dissertation), University of Arizona.
13. Snyder, F. F. (1938). "Synthetic Unit Graphs," *Trans. Am. Geophys. Union 19,* pp. 447-454.
14. Soil Conservation Service (1972). "National Engineering Handbook, Sec. 4, Hydrology."
15. U.S Army Corps of Engineers (1990). *HEC-1 Flood Hydrograph Package User's Manual.*
16. U.S. Geological Survey (1987). "Floods in Kansas and Techniques for Estimating Their Magnitude and Frequency on Unregulated Streams," *Water Resources Investigations Report 87-4008.*
17. Viessman, Warren Jr., and Lewis, Gary L. (1995). *Introduction to Hydrology,* pp. 182-185.
18. U.S. Soil Conservation Service (1986). "Urban Hydrology for Small Watersheds," *Technical Release 55*.

Appendix

Results of the Calibrations

Station 6813700

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	0.52	0.35	4.48	4.70	-4.7	4.80	1.1
2	0.46	0.48	6.83	6.15	11.2	1.15	-8.0
3	0.69	0.69	9.14	9.83	-7.0	1.50	0.0
4	0.66	0.57	3.40	2.83	20.1	3.50	-6.7
5	0.47	0.42	4.99	4.33	15.1	3.15	5.0
Average	**0.56**	**0.50**					

Station 6815700

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	0.85	0.77	27.64	27.61	0.1	5.30	0.1
2	0.61	0.77	34.15	34.55	-1.2	1.85	0.1
3	1.16	0.61	29.25	28.12	4.0	2.55	2.0
4	1.14	0.50	19.71	19.29	2.2	3.25	-7.1
5	1.03	0.77	55.17	52.00	6.1	3.00	0.0
6	1.49	0.82	68.90	64.91	6.2	3.80	-5.0
7	1.54	0.62	16.28	17.25	5.6	2.60	-5.5
8	1.17	0.60	15.63	17.25	10.2	7.95	9.7
9	1.23	0.77	74.62	92.78	20.0	4.60	2.2
10	1.02	0.66	37.69	34.89	8.0	1.65	-5.7
11	1.17	0.61	31.18	28.21	10.6	2.95	-1.7
12	1.54	0.62	16.28	17.25	5.6	2.60	-5.5
13	1.07	0.49	19.17	18.52	3.5	10.55	0.5
Average	**1.15**	**0.66**					

Station 6856800

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	2.58	0.54	13.17	11.72	12.3	3.95	-12.2
2	2.41	0.77	25.43	30.93	17.8	4.95	-1.0
3	2.57	0.60	11.89	11.55	2.9	9.75	0.0
Average	**2.52**	**0.64**					

Station 6864700

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	3.8	0.66	8.92	8.75	2.0	18.75	
2	3.58	0.46	19.97	22.17	-10.0	10.25	-2.4
Average	**3.69**	**0.56**					

Station 6879650

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	1.06	0.76	25.60	25.32	1.1	1.85	23.3
2	1.08	0.52	15.58	16.14	-3.6	8.05	3.9
Average	**1.07**	**0.64**					

Station 6887600

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	0.51	0.60	12.04	10.04	19.9	3.10	24.0
2	0.50	0.57	10.22	10.17	0.6	6.85	1.5
3	0.49	0.62	6.32	6.03	4.6	2.75	10.0
Average	**0.50**	**0.60**					

Station 6888900

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	0.96	0.60	10.90	12.23	-10.9	4.60	2.2
2	0.93	0.66	12.55	13.76	-8.8	7.50	0.0
3	0.83	0.62	7.99	7.42	7.6	2.20	-2.2
4	0.85	0.77	20.62	17.56	17.4	4.50	0.0
Average	**0.89**	**0.66**					

Station 6890700

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	0.51	0.54	7.16	6.83	4.8	5.00	5.3
2	0.53	0.54	6.71	5.66	18.5	2.05	-8.9
3	0.53	0.56	7.36	8.27	11.0	2.25	0.0
4	0.52	0.54	6.20	5.83	6.3	4.05	-4.7
Average	**0.52**	**0.55**					

Station 6912300

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	1.55	0.70	20.50	22.17	7.5	5.35	-2.7
2	1.39	0.82	29.51	32.85	-10.2	8.70	-0.6
3	0.75	0.77	99.12	87.23	0.1	3.25	0.0
4	0.51	0.77	70.32	66.61	5.6	1.90	8.6
Average	**1.05**	**0.77**					

Station 6913600

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	3.80	0.58	32.62	31.55	-3.4	7.30	4.0
2	3.59	0.44	20.53	23.22	11.6	14.25	-18.8
3	4.70	0.52	12.77	12.18	5.0	14.25	-7.5
4	4.65	0.53	32.23	35.54	-9.3	9.75	0.0
5	3.15	0.46	11.44	11.10	3.1	5.00	0.0
Average	**3.22**	**0.33**					

Station 6916700

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	0.51	0.77	63.72	66.61	-4.3	2.00	14.3
2	0.93	0.65	8.92	9.88	-0.1	1.90	-5.0
3	1.49	0.60	16.71	16.65	0.3	3.80	-5.0
4	1.07	0.62	19.68	17.25	14.2	3.40	-2.9
5	1.09	0.77	51.94	43.33	19.8	2.25	28.6
6	0.65	0.77	45.40	43.33	4.7	2.50	0.0
7	1.15	0.76	12.32	11.16	10.4	4.70	4.4
8	1.07	0.65	9.52	9.09	4.8	2.25	0.0
9	1.33	0.74	17.16	18.27	-6.0	3.35	3.1
10	1.59	0.74	9.60	9.74	-1.4	6.30	0.8
11	1.45	0.80	16.48	18.61	-11.3	7.10	1.4
12	1.20	0.60	17.16	18.27	-6.0	3.35	3.1
13	1.40	0.79	12.66	14.61	-13.0	3.35	-4.3
Average	**1.15**	**0.71**					

Station 7139700

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	2.02	0.54	16.31	14.90	9.5	5.55	5.7
Average	**2.02**	**0.54**					

Station 7142100

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	2.82	0.41	30.22	30.30	0.0	14.35	-1.0
2	2.97	0.55	21.78	21.04	3.5	6.50	0.0
3	2.54	0.42	40.33	35.12	14.8	5.90	-9.2
Average	**2.77**	**0.46**					

Station 7145300

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	1.84	0.46	32.43	30.87	5.1	4.00	0.0
2	1.72	0.48	32.11	31.15	3.1	2.90	-10.8
Average	**1.78**	**0.47**					

Station 7166200

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	2.21	0.57	20.33	18.04	12.7	3.00	-20.0
2	2.63	0.62	50.07	49.84	-0.4	7.05	-9.0
3	2.44	0.59	77.99	71.37	9.3	4.60	-3.2
4	2.76	0.69	24.13	24.38	-1.0	4.60	-8.0
5	2.39	0.63	23.00	23.96	-4.0	5.30	1.0
6	2.44	0.63	35.40	32.85	7.7	3.30	-17.5
7	2.96	0.64	39.62	40.78	-2.9	4.60	-3.2
8	3.03	0.57	18.41	17.84	3.1	2.25	9.8
9	2.38	0.52	92.52	81.56	13.5	11.85	12.9
10	2.63	0.6	37.47	45.60	-17.8	8.50	9.7
Average	**2.59**	**0.61**					

Station 7169200

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	1.87	0.76	97.93	99.54	1.6	5.20	4.0
2	1.88	0.75	141.91	150.10	-5.5	3.25	0.0
3	1.58	0.76	122.88	124.32	-1.2	2.35	4.4
4	2.05	0.77	80.49	73.63	9.3	4.10	2.5
5	1.92	0.76	36.82	32.99	-11.6	6.40	6.7
6	1.86	0.80	37.67	40.67	-7.6	3.20	-1.5
7	2.03	0.73	29.99	31.58	5.0	2.90	-3.3
8	2.20	0.81	33.87	33.98	-0.4	4.65	-2.1
Average	**1.93**	**0.77**					

Station 7169700

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	0.89	0.49	11.04	9.23	19.8	4.25	-0.1
2	1.02	0.60	7.59	7.53	0.6	1.60	-0.1
3	0.82	0.54	10.82	9.37	15.6	1.40	-0.1
4	0.84	0.61	17.42	17.25	1.1	1.50	-0.1
5	1.07	0.65	16.00	14.64	9.2	2.20	0.1
6	1.04	0.46	13.48	11.41	18.2	3.15	-0.1
Average	**0.95**	**0.56**					

Station 7182520

Event	T_{lag} (hr)	C_p	Computed Q_p (m^3/s)	Observed Q_p (m^3/s)	DQ_p %	Computed T_p (hr)	DT_p %
1	2.76	0.77	64.77	73.35	-11.7	7.40	18.4
2	3.62	0.80	46.05	55.17	16.5	5.75	0.0
3	3.72	0.80	34.35	38.37	10.5	6.30	5.0
4	2.72	0.81	46.76	46.44	17.7	8.55	0.6
5	3.64	0.81	73.04	83.83	-12.9	6.30	5.0
Average	**3.29**	**0.80**					