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FINAL REPORT

LAG TIMES OF URBAN AND DEVELOPING WATERSHEDS IN JOHNSON COUNTY, KANSAS

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Lawrence, Kansas

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16 Abstract

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Urbanization has a major impact on lag times. The lag time of a fully developed watershed is typically less than one-half of the lag time of the same watershed in an undeveloped state. Small urban watersheds with curb-and-gutter streets and storm sewers can have extremely short lag times. A 178-acre watershed in a single-family residential neighborhood was found to have a lag time of six minutes.

Two regression equations provide reasonable estimates of lag times for urban and developing watersheds within certain limitations. These equations apply to watersheds with curb-and-gutter streets and storm sewers in developed areas and no significant impoundments or detention sites. Two related equations provide estimates of times of concentration.

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Design, Drainage, Flood, GIS, Hydrograph, Lag Time, Urbanization and Watersheds.

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Final Report

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University of Kansas

A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

August 2001

PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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ABSTRACT

Design discharges for drainage structures in urban areas are often estimated by flood hydrograph simulation. Most computer programs for flood hydrograph simulation employ synthetic unit-hydrograph models that require lag time as input. The lag time must be estimated from the physical characteristics of the watershed. This study had two objectives: (1) to determine the lag times of gaged watersheds in the Kansas City area, and (2) to develop regression equations for estimating the lag times of urban and developing watersheds. Lag times were computed from gaging data for 85 significant events at 14 sites in Johnson County, Kansas. We estimated the average lag time for each watershed from the lag times for the individual events. Relevant physical characteristics of the streams and watersheds were computed from digital spatial data with Geographic Information Systems (GIS). Through multiple regression analysis, we identified significant explanatory variables and developed predictive relationships for lag time. The impervious area ratio and the road density were found to be suitable measures of urbanization.

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Two regression equations provide reasonable estimates of lag times for urban and developing watersheds within certain limitations. These equations apply to watersheds with curb-

and-gutter streets and storm sewers in developed areas and no significant impoundments or detention sites. Two related equations provide estimates of times of concentration.

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INTRODUCTION

1.1 Lag Times in Flood Hydrology

Design discharges for drainage structures in urban areas are often estimated by flood hydrograph simulation. Most computer programs for flood hydrograph simulation (e.g., the HEC-1 and HEC-HMS programs of the United States Army Corps of Engineers) employ synthetic unit-hydrograph models that require lag time as an input. The lag time must be estimated from the physical characteristics of the watershed.

In this study, lag time is defined as the time from the centroid of the unit net rainfall to the peak on the unit hydrograph. This definition is the one used in the synthetic unit hydrograph models of Snyder and Natural Resources Conservation Service (NRCS). The lag time is closely related to other measures of hydrologic response time such as the time of concentration. Time of concentration is defined as the time required for runoff to travel from the most remote point on the watershed boundary to the watershed outlet. According to theory, the time of concentration is approximately five-thirds of the lag time (McEnroe and Zhao, 1999). This approximation is incorporated in the NRCS hydrologic methods.

The time required for storm runoff to flow from one point to another point depends mainly on the length, average slope, and roughness of the flow path. Basin lag time can be related to various measures of the length, average slope, and roughness of the watershed or the main channel. Urbanization of a watershed generally results in a substantial reduction in lag time. The main cause of this reduction in lag time is the lower frictional resistance of the urban infrastructure (streets, parking lots, storm sewers, improved drainage channels, etc.) compared with the natural terrain.

Numerous formulas for lag time and time of concentration have been published over the years. The formulas fall into two categories: analytical formulas and regression models. Analytical formulas for lag time are necessarily based on greatly simplified representations of the watershed (e.g., sheet flow on a planar surface). Regression models relate observed lag times to watershed characteristics. All lag time formulas have limited ranges of applicability. K-TRAN Report KU-98-1 (McEnroe and Zhao, 1999) provides a review of lag time and time-of-concentration formulas for rural watersheds. Lag time formulas for urban watersheds have been developed by the United States Geological Survey (USGS, 1983) and others. The USGS formulas have very large standard errors that appear to be attributable to poorly chosen functional forms. Schulz and Lopez (1974) provide a comprehensive review of earlier research on urban lag times.

The authors investigated the lag times of small rural watersheds in Kansas in K-TRAN Project KU-98-1 (McEnroe and Zhao, 1999). The database for this study consisted of approximately a decade of 15-minute intervals of 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, estimated the average lag time for each watershed, and related the lag time to watershed characteristics by regression analysis. This research led to the following regression formula for the lag times of small rural watersheds in Kansas:

$$T_{lag} = 0.077\left(\frac{L}{\sqrt{S}}\right)^{0.66} \qquad (1.1)$$

in which T_{lag} is the lag time in hours, L is the length of the main channel, extended to the drainage divide, in km, and S is the average slope of the main channel.

The average slope of the main channel is defined as the elevation difference between two points on the channel, located 10 percent and 85 percent 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 22 percent. It is applicable to watersheds with drainage areas up to 50 km^2. Equation 1.1 is a corrected version of the equation published in the project report. The correction is explained in an errata sheet for Report No. K-TRAN: KU-98-1 dated October 2001.

1.2 Overview of Study

The present study had two objectives. The first objective was to determine the lag times of gaged watersheds in the Kansas City area. The second objective was to develop regression equations for estimating the lag times of urban and developing watersheds. Lag times were computed from gaging data for 85 significant events at 41 sites in Johnson County, Kansas. We estimated the average lag time for each watershed from the lag times for the individual events. Relevant physical characteristics of the streams and watersheds were computed from digital spatial data with GIS. Through multiple regression analysis, we identified significant explanatory variables and developed predictive relationships for lag time.

CHAPTER 2

PHYSICAL CHARACTERISTICS OF GAGED WATERSHEDS

2.1 Gage Sites

The gaged watersheds investigated in this study are located in eastern Johnson County, Kansas, which comprises the southwest quadrant of the Kansas City metropolitan area. The northern part of the study area has been fully developed since the 1950s. The central part of the study area includes a mixture of newer suburban developments and undeveloped land. The southern part of the study area is still primarily rural, but suburban development is proceeding rapidly.

The rainfall and water level data analyzed in this study were obtained from the data archives of the ALERT flood warning system administered by the city of Overland Park, Kansas (www.stormwatch.com). Fourteen sites with both rainfall and water-level gages were selected for study. Table 2.1 shows the locations of these sites. The watersheds of these 14 gaged sites range in size from 0.7 km^2 to 73 km^2 and in character from fully developed to largely undeveloped.

TABLE 2-1. Locations of Selected Gage Sites

Site ID	Site Name	Location
1200	USGS	Indian Creek at Marty Street
1300	Corporate Woods	Indian Creek at 109th Street
1400	Waterford	Indian Creek tributary at Neiman Road near 108th Street
1600	Hawthorne	Tomahawk Creek at Roe Avenue
1630	Switzer @ Tomahawk Cr	Tomahawk Creek at Switzer Road
1680	Wilshire Woods	Tomahawk Creek tributary at Grant Street near 127th St.
2120	Switzer @ Coffee Cr	Coffee Creek at Switzer Road
2140	Mission @ E. Camp Br	East Camp Branch at Mission Road
2160	175th @ Camp Branch	Camp Branch at 175th Street
2200	Mission @ Negro Cr	Negro Creek near Mission Road
2240	179th @ Wolf Cr	Wolf Creek at 179th Street
5600	JoCo Water	Brush Creek near Roe Drive
5700	Roeland Drive	Rock Creek at Roeland Drive
5800	Ward Parkway	Brush Creek at Ward Parkway

2.2 Digital Geospatial Data and GIS Procedures

Digital planimetric data for the selected watersheds were purchased from Johnson County's Automated Information Mapping System (AIMS) office. The data was provided as Arc/Info export files. We made extensive use of the INTR coverage of two-foot elevation contours, the CENT coverage of roadway centerlines, the BLDG coverage of building outlines, the EDGE coverage of street and parking lot edges, and the DRIV coverage of driveway centerlines. All of these coverages use a Stateplane coordinate system for the Kansas North Zone (3926) with an HPGN horizontal datum and units of feet. The digital soil data used in this study was the preliminary Soil Survey Geographic (SSURGO) data for Johnson County developed by the Natural Resources Conservation Service (NRCS). The soils data was downloaded from the Data Access and Support Center (DASC) of the state of Kansas at http://gisdasc.kgs.ukans.edu. The soil coverages were provided in a Universal Transverse Mercator (UTM) projection. We projected the coverages into the Stateplane coordinate system. All processing of the digital planimetric and soils data were performed with Arc/Info GIS. Many of these operations were performed with ARC Macro Language (AML) routines written by Professor C. Bryan Young of the University of Kansas (Young et al., 1999).

The first task in the analysis of the digital data was the delineation of the watershed boundaries and stream networks for the fourteen gages. Elevation grids for the subject areas were created from the INTR coverages of two-foot elevation contours. The grid-cell size was 12.2 meters. We used hydrologic functions in Arc/Info to fill the depressions in the elevation grids, to compute the flow-direction and flow-accumulation grids, and to generate polygon coverages of the watershed boundaries and line coverages of the streams. The threshold area for stream delineation was 0.24 km^2 (2000 cells).

2.3 Watershed Characteristics

Further analysis of the digital geospatial data with Arc/Info yielded several relevant watershed characteristics, which are listed and explained below:

i.) Drainage area (A), in km^2.

ii.) Length of the main channel (L), in km. The main channel is defined as the longest flow path in the watershed, extending from a point on the drainage divide to the watershed outlet (the location of the water-level gage).

iii.) Average slope of the main channel (S), in m/m. The average slope of the main channel is defined as the elevation difference between two points on the channel, located 10 percent and 85 percent of the channel length from the outlet, divided by the length of channel between the two points (75 percent of the total channel length).

iv.) Basin shape factor (Sh), defined as L^2/A, a dimensionless quantity.

v.) Soil texture classes present in the watershed, and the percentage of the drainage area covered by each soil texture class. Soil textures are classified by the system of the United States Department of Agriculture (USDA). The soils in the gaged watersheds are nearly all classified as silt loams (SiL) and silty clay loams (SiCL) in the USDA system.

vi.) Impervious area ratio (IA), defined as the fraction of the drainage area covered by impervious surfaces. Impervious areas were computed from the BLDG coverages of building outlines, the EDGE coverages of edges lines for roads and parking lots, and the DRIV coverages of driveway centerlines.

vii.) Road density (RD), in km^{-1}. Road density is defined as the total length of roads and streets in the watershed, divided by the drainage area. The total length of roads was computed from the CENT coverages of road centerlines.

Table 2-2 shows these characteristics for the 14 gaged watersheds.

2.4 Relationship between Road Density and Impervious Area Ratio

The impervious area ratio and the road density are two measures of the degree of urbanization. These two characteristics are strongly related. Figure 2-1 shows this relationship for the 14 gaged watersheds. The trend is essentially linear with two outliers: the watersheds of gages 1400 and 1680.

TABLE 2.2 Physical Characteristics of Gaged Watersheds

Site ID	Drainage Area (km^2)	Channel Length (km)	Basin Shape Factor	Channel Slope (m/m)	Soil Types (%) (SiL/SiCL/Other)	Imperv. Area Ratio	Road Density (km/km^2)
1200	69.17	23.97	8.31	0.00250	69 / 26 / 5	0.299	10.50
1300	60.05	20.77	7.18	0.00264	70 / 26 / 4	0.293	10.45
1400	13.83	6.23	2.81	0.00731	62 / 21 / 17	0.370	10.21
1600	52.81	18.53	6.50	0.00310	71/28/1	0.180	6.20
1630	15.05	8.99	5.37	0.00460	70 / 30 / 0	0.111	4.84
1680	0.72	1.48	3.04	0.01620	94 / 6 / 0	0.286	16.32
2120	36.03	14.31	5.68	0.00247	70 / 30 / 0	0.029	1.82
2140	10.88	5.48	2.76	0.01050	40 / 54 / 6	0.016	0.88
2160	17.70	10.28	5.97	0.00614	54 / 41 / 5	0.036	2.72
2200	13.51	8.05	4.80	0.00704	58 / 40 / 2	0.171	6.67
2240	73.40	17.69	4.26	0.00260	63 / 32 / 5	0.022	1.72
5600	6.58	3.67	2.05	0.01020	53 / 45 / 2	0.355	12.28
5700	7.17	4.71	3.09	0.00879	52 / 46 / 2	0.398	14.10
5800	35.27	7.87	1.76	0.00500	53 / 45 / 2	0.332	11.73

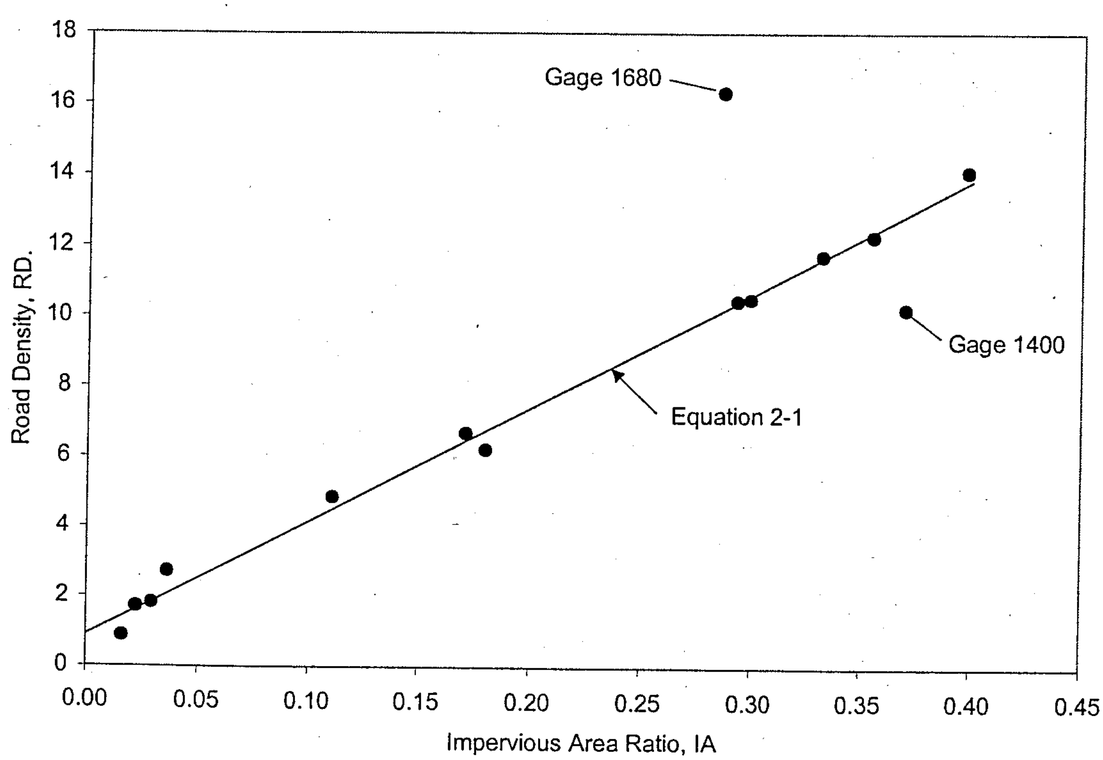

Figure 2.1 Relationship Between Road Density and Impervious Area Ratio

The watershed of Gage 1400 has an atypically large impervious area ratio for its road density. This watershed includes two major freeways, I-35 and I-435, and the interchange of these freeways. These freeways have much more impervious area per unit length of roadway than other types of streets.

The watershed of Gage 1680 is by far the smallest watershed in the data set, with a drainage area of only 0.73 km^2. The watershed is developed with single-family homes constructed in the 1980s. The impervious area ratio of 0.29 is a typical value for this land use, but the road density of 16.3 is atypically high. On this small watershed, road density appears to be a poor measure of the degree of urbanization. We suspect that road density may not be a reliable measure of urbanization for watersheds below a certain size. This issue merits further study.

The relationship between the road density and the impervious area ratio is approximated satisfactorily by the linear equation

$$RD = 0.9 + 32.4\ IA \qquad (2\text{-}1)$$

for RD in km^{-1}. This equation was fitted to the data points, excluding the two outliers, by least-squares regression.

Chapter 3

Lag Times of Gaged Watersheds

3.1 Selection of Storm Events

Rainfall and water level data for the selected ALERT system gages were provided by the city of Overland Park, Kansas. The data archives covered the period from 1996 to 1999. The raw data shows the exact time of each millimeter of accumulated rainfall and each incremental change in water level. We converted the rainfall records to equivalent records with fixed time intervals. We used a one-minute interval for Gage 1680 (the smallest watershed) and a three-minute interval for all other gages. In our initial scan of the records for the 14 gages, we selected 85 significant runoff events for further analysis. Figure 3.1 is a plot of the rainfall and water level data for one such event at Gage 1680.

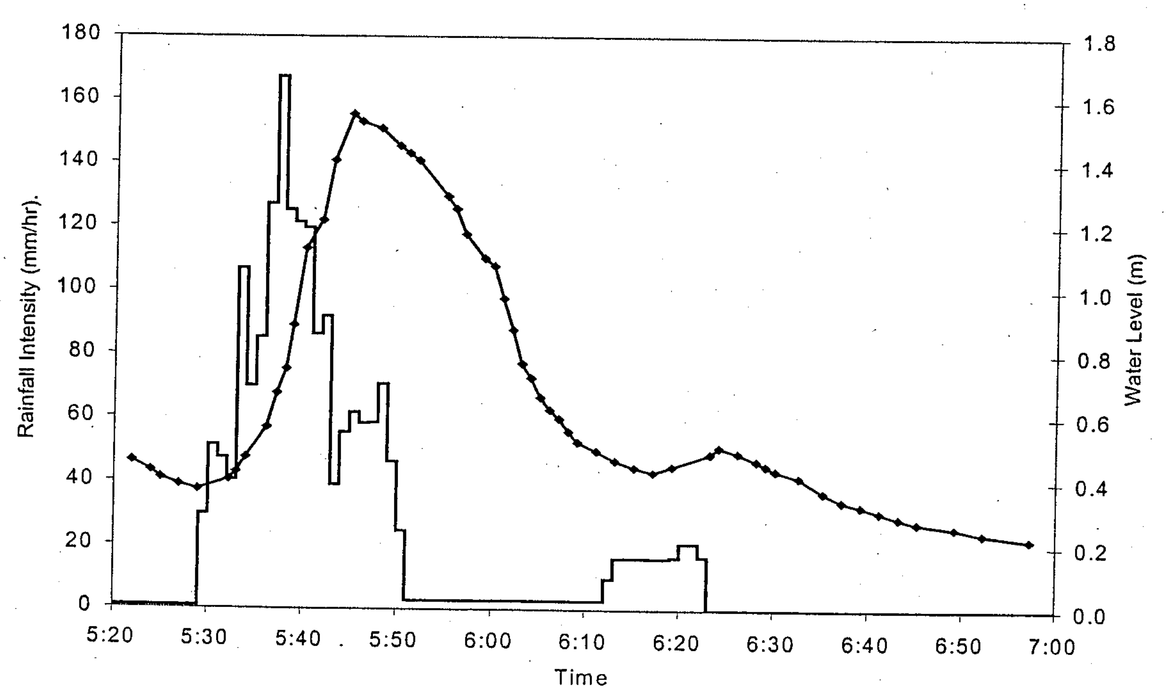

FIGURE 3.1 Event of 06/29/1998 at Gage 1680

3.2 Lag Times for Storm Events

Lag times for the selected events were determined from simulations with the HEC-1 flood hydrograph program of the U. S. Army Corps of Engineers. A simple HEC-1 model was created for each event. The rainfall recorded at the gage was applied to the entire watershed. The rainfall was partitioned into losses and direct runoff by the Green-Ampt method. Excess rainfall was transformed to streamflow by the unit-hydrograph method. Base flow was neglected.

Each watershed was assumed to contain two types of soils: silt loam and silty clay loam. Other soil types, if any, were apportioned to these two predominant soil types. Streamflow hydrographs for the portions of the watershed covered silt loams soils and silty clay loam soils were computed separately and then combined. The impervious surfaces were assumed to be distributed uniformly throughout the watershed. No losses were deducted from rainfall onto the impervious surfaces.

Table 3.1 shows the soil properties used in the HEC-1 models. The values of hydraulic conductivity and wetting-front suction are the average values for these soil types as reported by USDA Agricultural Research Service (Rawls, 1983). The values of the initial moisture deficit correspond to field capacity, a moderately moist condition. A sensitivity analysis indicated that the calibrated lag times are not sensitive to the assumed antecedent moisture condition.

TABLE 3.1 Soil Properties in HEC-1 Models for Lag-Time Calibration

Property	Soil Type	
	Silt Loam	Silty Clay Loam
Initial loss (mm)	2.5	2.5
Hydraulic conductivity (mm/hr)	6.6	1.0
Wetting-front suction (mm)	167	275
Initial moisture deficit (mm/mm)	0.22	0.13

Synthetic unit hydrographs were developed by Snyder's method, as implemented in HEC-1, using a peaking coefficient of 0.75. A Snyder unit hydrograph with a peaking coefficient of 0.75 has a shape very similar to the NRCS dimensionless unit hydrograph. A sensitivity analysis indicated that the calibrated lag times are not sensitive to the value of the peaking coefficient.

Lag time is an input to the unit-hydrograph component of the HEC-1 model. The lag time for each event was estimated initially, and then adjusted in successive simulations. The simulated hydrographs were compared with the actual water-level record for the event. The lag time was adjusted to cause the peak discharge on the simulated hydrograph occur at the same time as the actual peak water level at the gage. The calibration results for all selected events are presented in the Appendix. Table 3.2 shows an example HEC-1 data file.

TABLE 3.2 Example HEC-1 Data File

```
ID GAGE SITE ID 1680
ID EVENT OF JUNE 29, 1998
IT    1 29JUN98    0529     40
* ******
KK SUB1A
KM SILT LOAM SOIL
BA0.2613
PB    0
PI0.0195  0.0337  0.0311  0.0266  0.0701  0.0458  0.0560  0.0834  0.1097
PI0.0821  0.0796  0.0784  0.0566  0.0602  0.0255  0.0363  0.0404  0.0382
PI0.0383  0.0463  0.0303  0.0161
LG  0.1   0.217    6.6   0.26   28.6
UD0.0833
* ******
KK SUB1B
KM SILTY CLAY LOAM SOIL
BA  0.03
LG  0.1   0.129    11   0.04     0   28.6
UD0.0833
* ******
KK CP1
HC    2
* ******
ZZ
```

3.3 Average Lag Times for Gaged Watersheds

The lag times for the selected events at each gage were examined for consistency. The lag times were quite consistent at most gages. A few outliers were identified and discarded. The average lag times for the gaged watershed were computed from the lag times for the individual events. These average lag times are listed in Table 3.3.

TABLE 3.3 Average Lag Times of Gaged Watersheds

Site ID	Lag Time (hours)
1200	1.82
1300	1.68
1400	0.85
1600	1.30
1630	1.70
1680	0.10
2120	2.53
2140	1.19
2160	2.14
2200	1.02
2240	3.50
5600	0.24
5700	0.24
5800	0.75

3.4 Case Study: Wilshire Woods Watershed

The watershed of Gage 1680 "Wilshire Woods" deserves special attention. Its drainage area of 0.72 km^2 (178 acres) is a typical size for subbasins in urban flood models. All other gages in the ALERT system have much larger drainage areas. The Wilshire Woods watershed is a typical single-family residential neighborhood with curb-and-gutter streets and storm sewers. Located in southern Overland Park, Kansas, the watershed was developed in the 1980s. The impervious area ratio is 29 percent, a typical value for this type of development. Prior to development, silt loam soils covered 94 percent of the watershed and silty clay loam soils covered the other 6 percent. The longest flow path in the watershed has a length of 1.48 km and an average slope of 1.6 percent. This flow path has four components: a short run of overland flow across a lawn, a short run of shallow concentrated flow in a street gutter, approximately 1400 m of pipe flow in storm sewers, and approximately 30 m of open-channel flow between the storm-sewer outfall and the gage.

The Wilshire Woods watershed responds very rapidly to rainfall, as Figure 3.1 illustrates. In the event on June 29, 1998, the peak stage at the gage occurred only 7 minutes after the peak period of rainfall. The lag time for this event was determined to be 5 minutes. The lag times for the other eight selected events ranged from 5 to 8 minutes. The average lag time for the Wilshire Woods watershed is 6 minutes. The average time of concentration would be approximately five-thirds of the average lag time, or 10 minutes.

According to equation 1.1, a rural watershed in Kansas with the same channel length and slope as the Wilshire Woods watershed would have a lag time of approximately 25 minutes. The observed lag times for the developed watershed are only one-fourth of this value.

Chapter 4

Regression Equations for Lag Time

4.1 Impact of Urbanization of Lag Times

The impact of urbanization on lag time can seen by comparing the observed lag times with estimates of the lag times for rural conditions. The lag times of the gaged watersheds under rural conditions were estimated with equation 1.1. In Figures 4.1 and 4.2, the ratios of the observed lag times to the corresponding rural lag times are related to the two measures of urbanization: the impervious area ratio and the road density. In both cases, the trends can be approximated by exponential relationships.

The data points for Gages 1400 and 1600 are outliers. The lag time for Gage 1400 is unusually long. The watershed of Gage 1400 includes two major freeways, I-35 and I-435, and the interchange of these freeways. Differences between highway drainage and normal urban drainage could account for the long lag time. Storm runoff from highways is carried mainly in grass-lined ditches rather than in gutters and storm sewers. Highway ditches do not convey runoff as rapidly as gutters and storm sewers. Detention effects at interchanges can also be significant.

The lag time at Gage 1600, located at Tomahawk Creek at Roe Avenue, is unusually short. In fact, it is shorter than the lag time at Gage 1630, located at Tomahawk Creek at Switzer Road, which is approximately six miles upstream. This anomaly is attributable to the development pattern within the watershed. During the period of 1996 to 1999, the upper part of the watershed was mostly undeveloped and the lower part of the watershed was mostly developed. The timing of the peak flows at Gage 1600 is governed by runoff from developed areas near the gage. Because the lag times at Gages 1400 and 1600 are strongly affected by unusual conditions, these gages were omitted from the regression analyses.

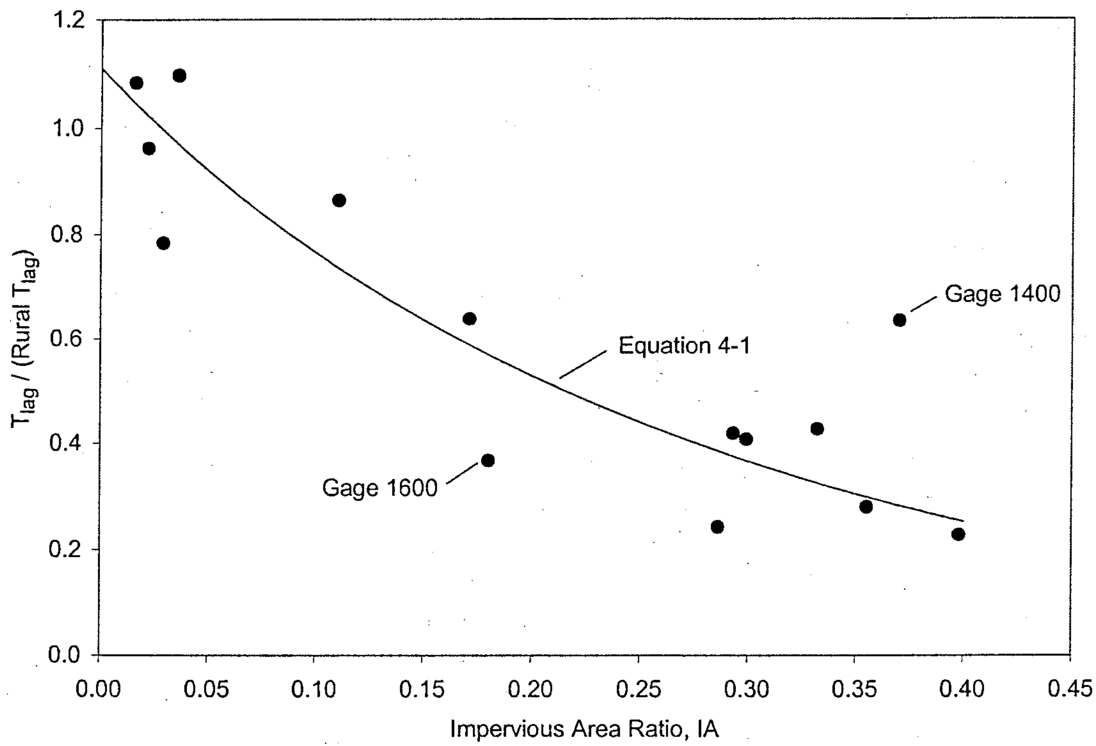

FIGURE 4.1 Impact of Impervious Area Ratio on Lag Time

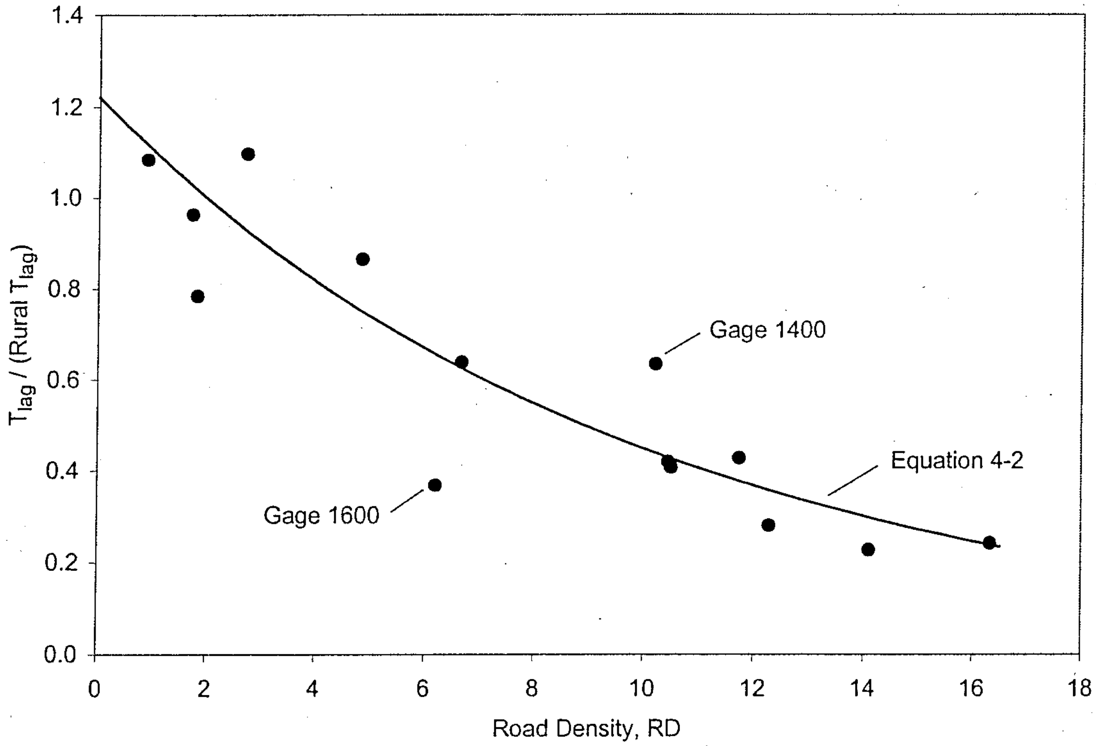

Figure 4.2 Impact of Road Density on Lag Time

Linear regression with the log of the lag-time ratio as the dependent variable and the impervious area ratio as the independent variable leads to relationship

$$\frac{T_{lag}}{\text{Rural } T_{lag}} = 1.11\, e^{-3.73\, IA} \qquad (4\text{-}1)$$

in which T_{lag} is the lag time and IA is the impervious area ratio. Linear regression with the log of the lag-time ratio as the dependent variable and the road density as the independent variable leads to relationship

$$\frac{T_{lag}}{\text{Rural } T_{lag}} = 1.22\, e^{-0.10\, RD} \qquad (4\text{-}2)$$

in which RD is the road density in km^{-1}.

4.2 Regression Analysis for Lag Time

From physical reasoning, the lag time of a watershed should be related to its size, shape, slope, and degree of urbanization. In the stepwise multiple regression analysis for lag time, the dependent variable was $\ln(T_{lag})$ and the seven independent variables were ln(A), ln(L), ln(S), ln (Sh), $\ln(L/S^{0.5})$, IA and RD, where A is the drainage area, L is the channel length, S is the average channel slope and Sh is the basin shape factor ($=L^2/A$). Table 4-1 shows the correlations among these variables.

TABLE 4.1 Correlation Matrix for Variables in Regression Analysis

	$\ln(T_{lag})$	ln(A)	ln(L)	ln(S)	ln(Sh)	$\ln(L/S^{0.5})$	IA	RD
$\ln(T_{lag})$	1.00							
ln(A)	0.72	1.00						
ln(L)	0.72	0.93	1.00					
ln(S)	-0.76	-0.79	-0.84	1.00				
ln(Sh)	0.56	0.59	0.83	-0.63	1.00			
$\ln(L/S^{0.5})$	0.70	0.94	0.99	0.80	-0.80	1.00		
IA	-0.73	-0.12	-0.16	0.26	-0.21	-0.12	1.00	
RD	-0.77	-0.22	-0.27	0.45	-0.24	-0.22	0.95	1.00

Many pairs of the independent variables, such as channel length and channel slope, are highly correlated. Regression equations with highly correlated independent variables tend to have unstable coefficients (i.e., coefficients with relatively large standard errors). This problem is avoided by using combined variables such as $L/S^{0.5}$ in the regression analysis. However, the combined variables should be physically meaningful. The combined variable $L/S^{0.5}$ is justified as follows. The time required for a flood wave to pass through a reach of channel with no lateral inflow is directly proportional to the reach length and inversely proportional to square root of the channel slope. Therefore, the travel time for a flood wave is directly proportional to $L/S^{0.5}$. Although a watershed is a much more complex system than a reach of channel, its lag time should also be related to $L/S^{0.5}$.

The two recommended regression equations for lag time both include the combined length-slope variable and a measure of urbanization as independent variables. These two equations are

$$\ln(T_{lag}) = -2.85 + 0.737 \ln\left(\frac{L}{\sqrt{S}}\right) - 3.51\,IA \qquad (4\text{-}3)$$

$$\ln(T_{lag}) = -2.24 + 0.637 \ln\left(\frac{L}{\sqrt{S}}\right) - 0.105\,RD \qquad (4\text{-}4)$$

or equivalently (after inverse logarithmic transformation)

$$T_{lag} = 0.058\left(\frac{L}{\sqrt{S}}\right)^{0.74} e^{-3.5\,IA} \qquad (4\text{-}5)$$

$$T_{lag} = 0.106\left(\frac{L}{\sqrt{S}}\right)^{0.63} e^{-0.10\,RD} \qquad (4\text{-}6)$$

for T_{lag} in hours, L in km, S in m/m and RD in km^{-1}. Equation 4-3 has a standard error (S_e) of 0.190 log units and a coefficient of determination (R^2) of 0.976. Equation 4-4 has a standard error of 0.165 log units and a coefficient of determination of 0.982. The equivalent standard error ranges for equations 4-5 and 4-6 can be expressed in percentage terms. These ranges are (+21 percent, -17 percent) for equation 4-5 and (+18 percent, -15 percent) for Equation 4-6. Table 4.2 shows the standard errors of the coefficients in Equations 4-3 and 4-4.

Table 4.2 Standard Errors of Coefficients in Equations 4-3 and 4-4

	Equation 4-3		Equation 4-4	
Quantity	S_e	S_e/value	S_e	S_e/value
Intercept	0.293	-0.10	0.290	-0.13
Coefficient of ln($L/S^{0.5}$)	0.054	0.07	0.051	0.08
Coefficient of RD	0.408	-0.12	0.010	-0.10

In Figures 4.3 and 4.4, lag-time estimates from Equations 4-5 and 4-6 are compared with the observed lag times for the gaged watersheds, including gages 1400 and 1600.

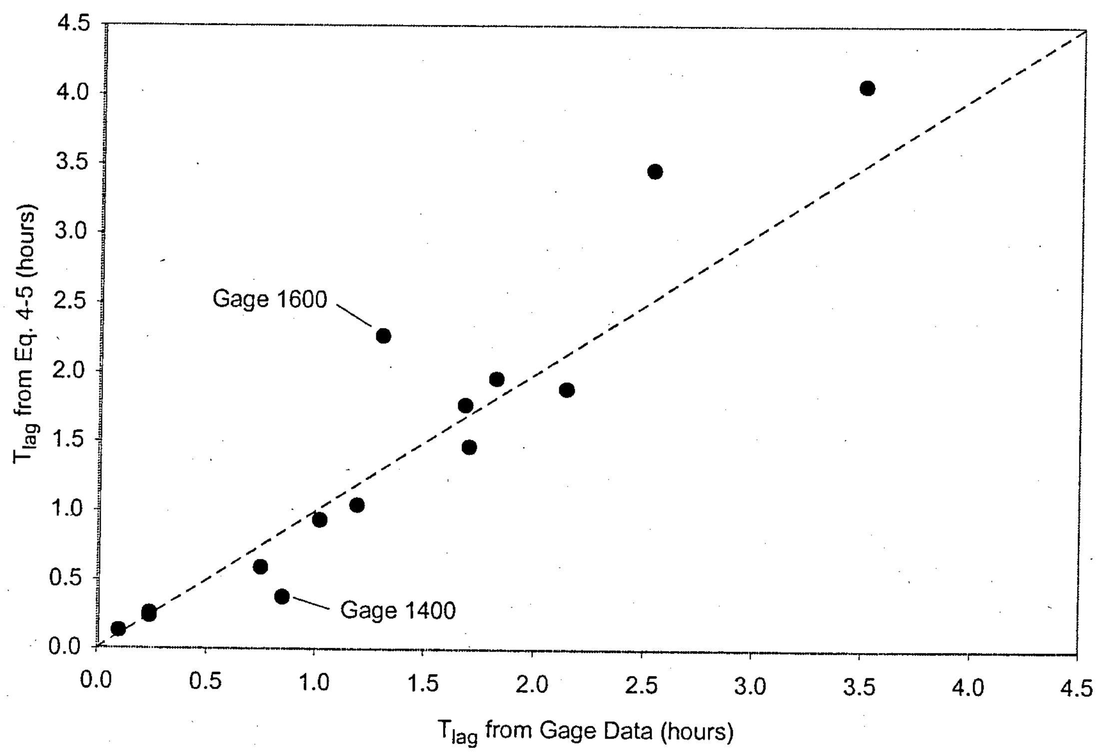

Figure 4.3 Comparison of Lag Times from Equation 4-5 and Gage Data

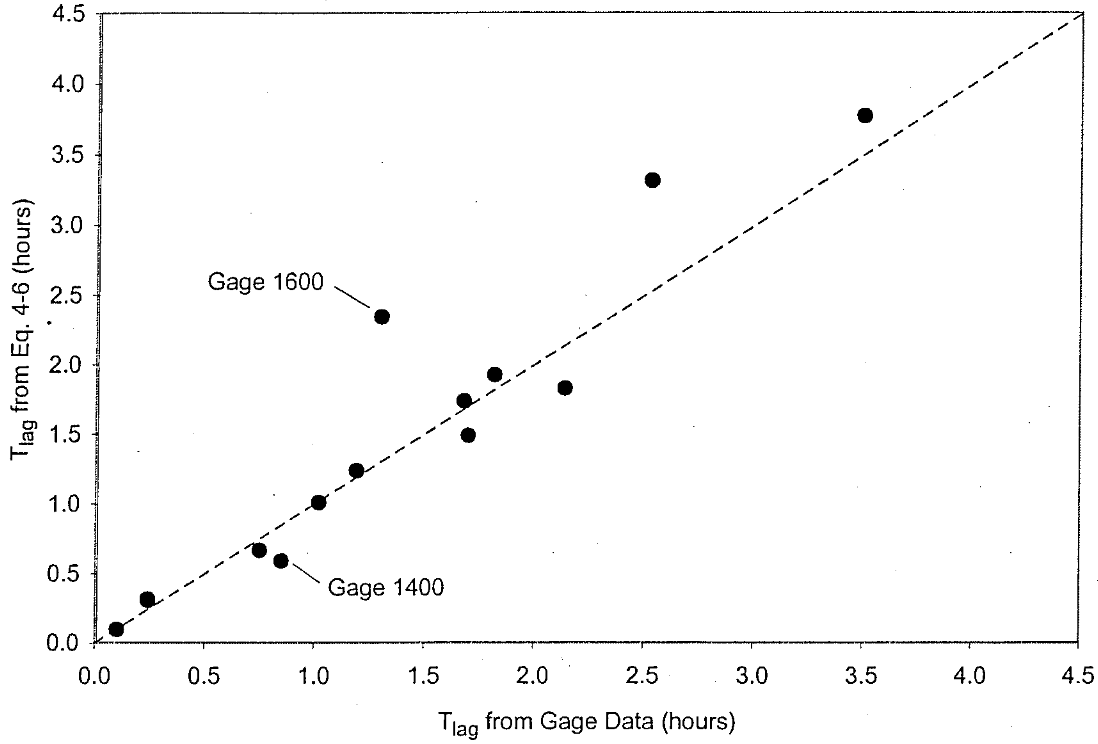

Figure 4.4 Comparison of Lag Times from Equation 4-6 and Gage Data

The time of concentration of a watershed is approximately five-thirds of the lag time (McEnroe and Zhao, 1999). Equations 4-5 and 4-6 for lag time can be multiplied by five-thirds to obtain the following equations for the time of concentration, T_c:

$$T_c = 0.097\left(\frac{L}{\sqrt{S}}\right)^{0.74} e^{-3.5\,IA} \qquad (4\text{-}7)$$

$$T_c = 0.177\left(\frac{L}{\sqrt{S}}\right)^{0.63} e^{-0.10\,RD} \qquad (4\text{-}8)$$

for T_c in hours, L in km, S in m/m and RD in km^{-1}.

4.3 Use and Limitations of the Regression Equations

Equations 4-5 through 4-8 yield reasonable estimates of lag time and time of concentration when applied correctly to appropriate watersheds. The limitations on their use are as follows:

1.) The values of the inputs to the equations should be within the ranges for the gaged watersheds, as shown in Table 4.3. These inputs must be computed in accordance with the definitions in Section 2.3.

Table 4.5 Recommended Ranges for Inputs to Equations 4-5 through 4-8

Variable	Range
$L/S^{0.5}$ (km)	12 – 480
IA	0.02 – 0.40
RD (km^{-1})	1 – 16

2.) The watershed should not contain any lakes, ponds or detention sites that would substantially alter the flood hydrographs. Equations 4-5 through 4-8 would tend to underestimate the lag times and times of concentrations of watersheds with significant storage impacts.

3.) The developed areas of the watershed should have curb-and-gutter streets and storm sewers. Equations 4-5 through 4-8 would tend to underestimate the lag times and times of concentration of developed areas with roadside ditches.

4.) The channel conditions should be within the normal range for the overall level of urbanization. The equations do not explicitly account for channel improvements. In each regression equation, a single input serves as an overall measure of development-related impacts, including channel improvements.

5.) The urban development within the watershed should be reasonably well distributed. Equations 4-5 through 4-8 would tend to overestimate the lag time and time of concentration of a watershed that is highly urbanized at the lower end and undeveloped elsewhere.

6.) These equations should be applicable to watersheds throughout the Midwestern United States, provided that the other limitations are met.

7.) Equation 1-1 may provide better estimates of lag time than Equations 4-5 and 4-6 for watersheds with very little development ($IA < 0.03$ or $RD < 2$).

Chapter 5

Conclusions

The major findings from this research are as follows:

1. Urbanization has a major impact on lag times. The lag time of a fully developed watershed is typically less than one-half of the lag time of the same watershed in an undeveloped state.

2. Small urban watersheds with curb-and-gutter streets and storm sewers can have extremely short lag times. A 178-acre watershed in a single-family residential neighborhood was found to have a lag time of six minutes.

3. A regression model for lag times of urban and developing watersheds must include a measure of urbanization as an independent variable. Two suitable measures of urbanization are the impervious area ratio and the road density.

4. Equations 4-5 and 4-6 provide reasonable estimates of lag times for urban and developing watersheds, subject to the limitations listed in Section 4-3. These equations apply to watersheds with curb-and-gutter streets and storm sewers in developed areas and no significant impoundments or detention sites.

5. Times of concentration of urban and developing watersheds can be estimated with Equations 4-7 and 4-8. These equations have the same limitations as the equations for lag time.

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Appendix

Calibration Results for Gaged Watersheds

Gage 1200

Event	Date	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	11/30/98	2.32	2.30	1.80	2.91
2	10/04/98	3.08	3.00	1.90	3.40
3	9/28/98	4.45	4.45	2.05	1.67
4	8/26/98	2.07	2.10	1.80	1.81
5	7/29/98	6.05	6.00	1.80	2.66
6	6/29/98	1.95	2.00	1.60	2.60
Average				1.82	

Gage 1300

Event	Date	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	5/31/99	2.68	2.70	1.90	0.63
2	5/21/99	2.18	2.20	1.70	0.69
3	4/22/99	1.90	1.90	1.60	1.87
4	7/29/98	5.90	5.90	1.75	3.40
5	7/26/98	3.70	3.70	1.45	2.23
Average				1.68	

Gage 1630

Event	Date	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	6/22/98	6.30	6.30	1.80	2.24
2	6/15/98	1.60	1.60	1.50	1.48
3	5/05/98	2.10	2.10	1.75	1.47
4	2/25/98	2.95	3.00	1.80	0.54
5	8/26/98	1.80	1.80	1.55	1.17
6	8/27/98	2.10	2.10	1.80	0.96
7	9/13/98	10.30	10.30	1.70	1.89
Average				1.70	

Gage 1680

Event	**Date**	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	5/17/99	0.20	0.20	0.10	0.25
2	11/29/98	0.85	0.85	0.10	0.43
3	10/04/98	0.37	0.35	0.13	0.78
4	8/26/98	1.07	1.05	0.10	0.45
5	6/29/98	1.73	1.75	0.08	1.55
6	5/05/98	0.80	0.80	0.10	0.39
7	2/25/98	0.12	0.15	0.10	0.30
8	9/22/97	0.33	0.35	0.10	0.32
9	5/18/97	0.27	0.30	0.08	0.46
Average				0.10	

Gage 2120

Event	**Date**	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	5/17/99	2.90	2.90	2.55	2.90
2	5/04/99	5.95	5.95	2.75	3.39
3	5/30/97	3.90	3.90	2.30	1.16
Average				2.53	

Gage 2140

Event	**Date**	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	5/03/99	1.83	1.80	1.15	2.22
2	4/26/99	4.45	4.45	1.17	2.39
3	12/06/98	3.82	3.80	1.19	1.87
4	11/30/98	3.81	3.80	1.13	1.85
5	11/01/98	10.10	9.95	1.32	2.30
6	10/04/98	5.30	5.25	1.18	2.72
Average				1.19	

Gage 2160

Event	Date	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	12/06/98	7.45	7.45	2.35	0.93
2	11/30/98	4.15	4.15	2.20	0.85
3	11/01/98	4.37	4.37	1.90	1.26
4	10/04/98	5.15	5.15	2.00	1.63
5	5/31/98	8.80	8.82	2.25	0.84
6	5/30/97	3.08	3.00	2.15	0.66
Average				2.14	

Gage 2200

Event	Date	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	6/11/99	1.75	1.75	1.05	1.09
2	6/01/99	1.85	1.85	1.01	1.28
3	7/29/98	5.50	5.50	1.01	1.50
4	7/03/98	2.00	2.00	1.02	1.76
5	6/15/98	2.30	2.30	1.02	0.79
6	9/13/97	1.23	1.23	1.00	2.21
Average				1.02	

Gage 2240

Event	Date	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	11/30/98	6.00	6.00	3.60	3.79
2	10/04/98	6.65	6.67	3.40	5.42
3	7/30/98	6.40	6.40	3.50	4.05
Average				3.50	

Gage 5600

Event	**Date**	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	9/29/98	0.95	0.95	0.20	0.59
2	6/05/96	1.17	1.15	0.20	0.49
3	6/24/96	1.40	1.40	0.25	1.29
4	7/21/96	1.10	1.10	0.27	0.37
5	7/29/96	0.50	0.50	0.25	1.22
6	11/16/96	0.80	0.80	0.25	0.34
7	6/12/97	1.00	1.00	0.25	0.35
8	7/11/97	0.80	0.78	0.25	0.63
Average				0.24	

Gage 5700

Event	**Date**	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	5/31/99	0.32	0.30	0.25	1.97
3	11/29/98	0.93	0.95	0.20	2.79
4	10/28/98	1.38	1.40	0.25	1.94
5	7/11/97	1.17	1.20	0.20	3.96
6	6/12/97	0.25	0.25	0.20	1.57
7	10/07/96	1.18	1.15	0.35	1.45
8	8/26/96	0.32	0.30	0.20	1.20
9	7/30/96	0.48	0.50	0.20	2.74
10	6/24/96	1.38	1.35	0.25	3.59
Average				0.24	

Gage 5800

Event	**Date**	Actual Time to Peak (hr)	Simulated Time to Peak (hr)	Calibrated Lag Time (hr)	Peak Water Level (m)
1	5/31/99	1.17	1.15	0.85	1.48
2	4/22/99	0.82	0.85	0.70	2.70
3	11/29/98	1.61	1.60	0.75	2.45
4	5/17/99	2.40	2.40	0.70	1.50
Average				0.75	