Lagtime Relations for Urban Streams in Georgia

By Ernest J. Inman

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ABSTRACT

Urban flood hydrographs are needed for the design of many highway drainage structures, embankments, and entrances to detention ponds. The three components that are needed to simulate urban flood hydrographs at ungaged sites are the design flood, the dimensionless hydrograph, and lagtime. The design flood and the dimensionless hydrograph have been presented in earlier studies for urban streams in Georgia. The objective of this study was to develop equations for estimating lagtime for urban streams in Georgia.

Lagtimes were computed for 329 floods at 69 urban gaging stations in 11 cities in Georgia. These data were used to compute an average lagtime for each gaging station. Multiple regression analysis was then used to define relations between lagtime and certain physical basin characteristics, of which drainage area, slope, and impervious area were found to be significant. A qualitative variable was used to account for a geographical bias in flood-frequency region 4, a small area of southwestern Georgia.

Information from this report can be used to simulate a flood hydrograph using a dimensionless hydrograph, the design flood, and the lagtime obtained from regression equations for any urban site with less than a 25-square-mile drainage area in Georgia.

INTRODUCTION

The design of highway bridges and culverts typically includes an evaluation of the flood-related risks associated with the design. These risks can be divided into three categories: (1) direct damages to the roadway and bridge; (2) traffic-related losses, such as extra miles necessary due to detours; and (3) flood damage in the upstream floodplain, such as inundation of upstream buildings and structures (Schneider and Wilson, 1980). In order to quantify traffic-related losses and upstream floodplain damage, the length of time that a site is inundated is required. This type of analysis requires flood hydrographs for the particular site.

Another specific use of an estimated flood hydrograph is in the design of detention ponds in urban areas. Most cities require detention ponds to detain the additional runoff resulting from urbanization; to accomplish this purpose, a simulated flood hydrograph for a design flood is needed at the entrance of a detention pond. The size of the detention pond and outlet structure can be designed by other methods.

For ungaged sites, flood hydrograph information is difficult to obtain; therefore, a method is needed to estimate the flood hydrograph associated with a design peak discharge. Recognizing this need, the U.S. Geological Survey (USGS), in cooperation with the Georgia Department of Transportation, began an investigation in 1998 to develop such a method.

Purpose and Scope

This report describes the results and methods used to develop regression equations for estimating lagtime for any urban site in Georgia. Lagtime is generally defined as the time from the center-of-mass of rainfall excess to the center-of-mass of the resultant runoff hydrograph. When basins are modified by impervious cover, lagtime usually becomes shorter. This report also demonstrates the use of lagtime for estimating design-flood hydrographs as described by Inman (1986). The scope of this study includes selected urban basins of 25 square miles (mi^2) or less within the State of Georgia.

Lagtime estimating equations were developed for urban streams in the metropolitan Atlanta, Ga., area as part of the Inman (1986) study. However, the equations might not be applicable for the remainder of the State because there are only 19 stations in the Atlanta area; thus, the data base is much too small to provide relations for the entire State. The lagtime equations in this study supersede the lagtime equations in the Inman (1986) study.

Acknowledgments

The guidance and technical assistance of several USGS hydrologists, particularly Vernon B. Sauer, are recognized and greatly appreciated. Also, the computer programming contributions of USGS hydrologist Steven E. Ryan (deceased) were invaluable to this study.

DATA BASE

The data used in this study for the regression analysis of lagtime came from 69 urban stations in 11 cities throughout Georgia. The locations of cities with gages and the number of gages in each city are shown in figure 1. The cities and number of gages in each city are Albany-2, Athens-6, Atlanta-19, Augusta-6, Columbus-4, Moultrie-4, Rome-6, Savannah-4,

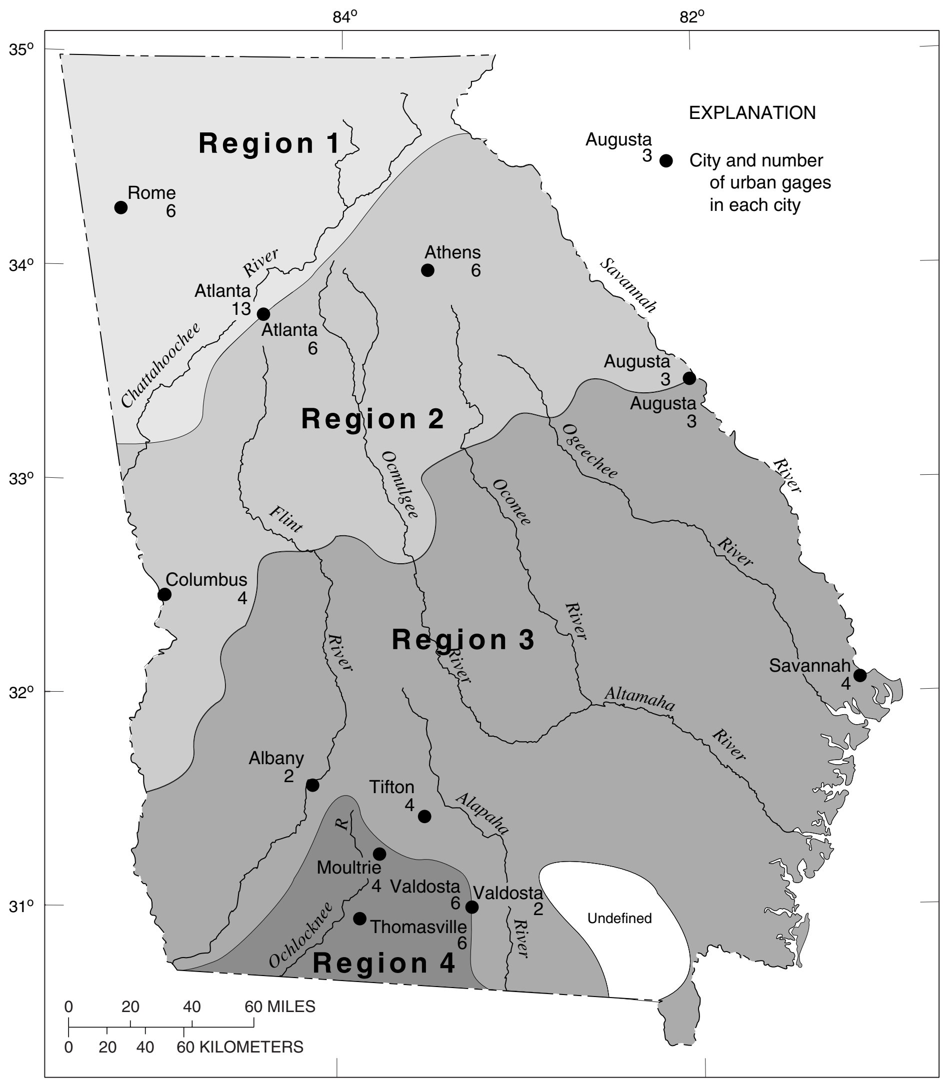

Figure 1. Rural flood-frequency regions in Georgia, cities where gaging stations were used in this study, and number of gages in each city. Some cities have gaging stations in more than one region. See table 2 (p. 6–7) for gages and regions.

Thomasville-6, Titon-4, and Valdosta-8. A total of 329 floods were selected from these 69 stations by reviewing the rainfall-runoff hydrographs that were plotted for use in other urban-related studies. The selection criteria were: (1) uniform, relatively short-duration rainfall; and (2) a simple (noncompound) discharge hydrograph. Both rainfall and discharge data at 5-minute intervals were available for these floods.

HYDROGRAPH-SIMULATION PROCEDURE

Several traditional methods were considered for simulating a hydrograph for a flood of a selected recurrence interval at the outlet of an ungaged watershed. However, the dimensionless hydrograph procedure based on observed data from 61 rural basins and 19 Atlanta urban basins developed by Inman (1986) was used for this study and is summarized below.

Method Summary

A statewide dimensionless hydrograph was developed by Inman (1986) for use in urban basins up to 25 mi^2 and rural basins up to 500 mi^2 (fig. 2; table 1). Peak discharge and lagtime are necessary parameters to convert the dimensionless hydrograph to a simulated hydrograph. The simulated hydrograph should be considered a typical, or average, hydrograph for the design peak discharge. It is not intended to reproduce actual runoff hydrographs.

Stamey and Hess (1993) presented a technique for estimating peak discharges for selected recurrence intervals for rural basins in Georgia. Inman (1995) presented a technique for estimating peak discharges for selected recurrence intervals for urban basins up to 25 mi^2 in Georgia.

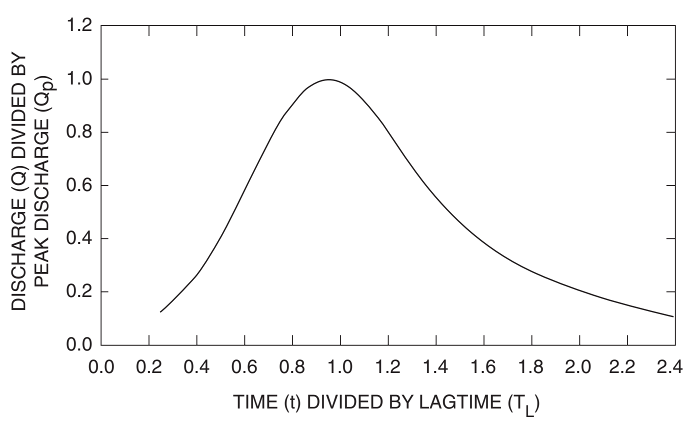

Figure 2. Statewide dimensionless hydrograph.

Lagtime is computed as the time at the centroid of the unit hydrograph minus one-half the time of the computation interval (duration). The unit hydrograph computation method was described by O'Donnell (1960).

Table 1. Time and discharge rations for the statewide dimensionless hydrograph

[t/T_L, time in hours divided by lagtime in hours; Q/Q_p, discharge in cubic feet per second divided by peak discharge in cubic feet per second]

Time ratio (t/T_L)	Discharge ratio (Q/Q_p)
0.25	0.12
.30	.16
.35	.21
.40	.26
.45	.33
.50	.40
.55	.49
.60	.58
.65	.67
.70	.76
.75	.84
.80	.90
.85	.95
.90	.98
.95	1.00
1.00	.99
1.05	.96
1.10	.92
1.15	.86
1.20	.80
1.25	.74
1.30	.68
1.35	.62
1.40	.56
1.45	.51
1.50	.47
1.55	.43
1.60	.39
1.65	.36
1.70	.33
1.75	.30
1.80	.28
1.85	.26
1.90	.24
1.95	.22
2.00	.20
2.05	.19
2.10	.17
2.15	.16
2.20	.15
2.25	.14
2.30	.13
2.35	.12
2.40	.11

TESTING OF DIMENSIONLESS HYDROGRAPH

Four tests generally are required to establish the soundness of hydrologic models. The first test is the standard error of estimate, followed by verification, bias, and sensitivity; these were described by Inman (1986).

Additional Verification and Bias Testing

As other states also completed studies of simulating flood hydrographs, it became apparent that the Georgia dimensionless hydrograph could be used over a widespread area of the Southeastern United States. Olin and Atkins (1988) tested the Georgia dimensionless hydrograph using both urban and rural Alabama data and showed that the Georgia dimensionless hydrograph was appropriate for use in Alabama. Neely (1989) tested the Georgia dimensionless hydrograph using both urban and rural data in Arkansas and showed that the Georgia dimensionless hydrograph fit Arkansas observed data better than a dimensionless hydrograph developed using Arkansas data.

Becker (1990) used the Georgia procedure to develop a dimensionless hydrograph for Missouri, using both urban and rural data, and showed that the Georgia dimensionless hydrograph was 4.4 percent wider at 50 percent of peak flow and 7.3 percent wider at 75 percent of peak flow. Becker (1990) stated that the minor differences between the two dimensionless hydrographs were the result of the different hydrologic settings of basins in Missouri and Georgia.

Mason and Bales (1996) used the Georgia procedure to develop a dimensionless hydrograph for North Carolina using local urban data only. They then used the North Carolina and Georgia dimensionless hydrographs to simulate 96 hydrographs for 29 North Carolina basins. The results showed that at 50 percent of peak flow, the Georgia standard error of estimate was 0.4 percent higher than the North Carolina estimate; and for 75 percent of peak flow, the Georgia estimate was 0.1 percent higher than the North Carolina estimate. Based on these results, the Georgia and North Carolina dimensionless hydrographs can be applied to the Piedmont, Sand Hills, and Coastal Plain physiographic provinces of North Carolina.

Sherwood (1993) verified the Georgia dimensionless hydrograph for use on both urban and rural basins in Ohio. Sherwood (1993) stated that the errors at 50 percent and 75 percent of peak flow for the Ohio data were comparable to the errors for the Georgia data.

Robbins (1986) used the procedure developed in Georgia to develop a dimensionless hydrograph for central Tennessee using both urban and rural data. After extensive testing and comparing, Robbins concluded that the Georgia dimensionless hydrograph provided a better fit for the Tennessee data.

Caution should be exercised, however, when using the Georgia dimensionless hydrograph in the lower Coastal Plain (region 3). In this region, continuous records are lacking for streams with extremely flat slopes. As a result, the Georgia dimensionless hydrograph was developed without using data from streams having channel slopes that average about 10 feet per mile or less. Consequently, for slopes of less than 5–10 feet per mile, a simulated hydrograph width could be underestimated.

REGRESSION ANALYSIS OF LAGTIME

To estimate lagtime for ungaged urban sites, the average station lagtimes obtained from the 69 stations used in this study were related to their basin characteristics. This was done using the linear multiple-regression method described by Riggs (1968).

The regression equations provided a mathematical relation between the dependent variable (lagtime) and the independent variables (the basin characteristics found to be statistically significant). All variables were transformed into logarithms before analysis to obtain a linear regression model, and to achieve equal variance about the regression line throughout the range (Riggs, 1968, p. 10). A 95-percent confidence limit was specified in the analysis to select the significant independent variables.

The regression analyses were performed using procedures available in the “Statistical Analysis System” (SAS) (SAS Institute, Inc., 1989). The six specific SAS analyses performed were: (1) backward elimination; (2) stepwise regression, forward and backward; (3) MAXR—forward selection with pair switching; (4) MINR—forward selection with pair searching; (5) forward searching; and (6) GLM—plots of predicted and observed peaks, and residuals and significant parameters.

Selected independent variables, or physical basin characteristics, that were tested for significance are defined in the following paragraphs and listed for each station in table 2.

Lagtime (T_L)—The elapsed time, in hours from the centroid of rainfall excess to the centroid of the resultant runoff hydrograph. Lagtime is computed from the unit hydrograph.

Drainage area (DA)—Area of the basin, in square miles, planimetered from USGS 7 1/2-minute topographic maps. All basin boundaries were field checked.

Channel length (L)—The length of the main channel, in miles, as measured from the gaging station upstream along the channel to the basin divide.

Channel slope (S)—The main channel slope, in feet per mile, as determined from USGS 7 1/2-minute topographic maps. The main channel slope was computed as the difference in elevation, in feet, at the 10- and 85-percent points divided by the distance, in miles, between the two points.

Measured total impervious area (TIA)—The percentage of drainage area that is impervious to infiltration of rainfall. This parameter was determined by a grid-overlay method using 1972–94 aerial photography (obtained from the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service). According to Cochran (1963), a minimum of 200 points, or grid intersections, per area or subbasin provides a confidence level of 0.10. Three counts of at least 200 points per subbasin were obtained and the results averaged for the final value of measured total impervious area. For several of the larger basins where some development occurred during the period of data collection, this parameter was determined from aerial photographs taken in 1972 (near the beginning of data collection), and then averaged with the values obtained from aerial photography taken in 1978 (near the end of data collection).

$L/(S)^{0.5}$—A ratio, where L and S have been previously defined.

Rural lagtime (RT_L)—The lagtime, in hours, for an equivalent rural drainage basin. The equivalent rural lagtimes were computed from regression equations developed by Inman (1986).

Regionalization

The initial regressions were run separately for each of the four flood-frequency regions (fig. 1) delineated by Stamey and Hess (1993). The regressions for regions 1, 3, and 4 did not show more than one independent variable significant at the 95-percent confidence limit. Region 2 had three independent variables—DA, TIA, and S—which were significant at the 95-percent confidence limit.

Another regression was run that combined all 69 stations into one analysis. This combined regression showed that DA, TIA, and S were significant at the 95-percent confidence limit. However, the predicted lagtimes in region 4 were consistently positive, indicating that the predicted lagtimes were greater than the observed lagtimes. Therefore, a qualitative variable was established to account for the apparent bias in region 4. This qualitative variable (QV) was set equal to 10 if the site was in region 4, and set to 1 if the site was in any of the other regions. All variables were transformed to logarithms, and the regression analysis was re-run with the qualitative variable as an independent variable. The final statewide equation resulting from this analysis is

$$T_L = 7.86DA^{0.35}TIA^{-0.22}S^{-0.31}QV^{-0.11} .$$

For regions 1, 2, and 3, where QV=1, the above equation reduces to

$$T_L = 7.86DA^{0.35}TIA^{-0.22}S^{-0.31} .$$

For region 4, where QV=10, the equation algebraically reduces to

$$T_L = 6.10DA^{0.35}TIA^{-0.22}S^{-0.31} .$$

The accuracy of regression equations can be expressed by three standard statistical measures: (1) the coefficient of determination, R-square (the correlation coefficient squared); (2) the standard error of regression; and (3) the standard error of prediction. R-square measures the amount of variation in the dependent variable that can be accounted for by the independent variables. For example, an R-square of 0.88 indicates that 88 percent of the variation is accounted for by the independent variables and

Table 2. Selected basin characteristics for statewide urban lagtime study sites, by city

[t_L, lagtime in hours; DA, drainage area, in square miles; L, channel length, in miles; S, main channel slope, in feet per mile; TIA, area that is impervious to infiltration of rainfall, in percent; $L/(S)^{0.5}$, a ratio where L and S have been previously defined; RT_L, rural lagtime, in hours, for an equivalent rural drainage basin in the same hydrologic area as the urban basin (Inman, 1986); R, flood-frequency region where the basin is located (Stamey and Hess, 1993)]

Station number	Basin characteristics							
	T_L	DA	L	S	TIA	$L/(S)^{0.5}$	RT_L	R
Albany								
02352605	0.87	0.16	0.58	33.3	28.8	0.10	2.09	3
02352964	0.71	0.05	0.36	22.5	11.1	0.08	1.43	3
Athens								
02217505	0.55	1.44	1.89	91.6	40.2	0.20	2.15	2
02217506	0.46	0.19	0.75	214.0	31.0	0.05	0.67	2
02217730	0.64	0.30	0.70	106.0	35.6	0.80	0.97	2
02217750	0.42	0.35	0.90	122.0	38.1	0.08	1.01	2
02217905	0.37	0.42	0.76	158.0	61.6	0.07	1.05	2
02217990	0.60	0.30	1.04	102.0	33.7	0.10	0.97	2
Atlanta								
02203820	3.81	8.67	7.58	28.0	30.5	1.43	6.64	2
02203835	1.41	3.43	2.66	61.0	25.6	0.34	3.58	2
02203845	0.83	0.84	1.93	67.6	30.6	0.24	1.76	2
02203850	2.06	7.50	5.91	34.8	28.2	1.00	5.91	2
02203870	2.18	3.68	3.95	37.5	25.8	0.64	4.10	2
02203884	1.21	1.88	2.22	74.1	26.7	0.26	2.56	2
02336080	6.41	19.10	7.43	16.0	31.4	1.86	11.0	1
02336090	0.71	0.32	1.12	129.0	19.0	0.10	0.96	1
02336102	1.27	2.19	2.50	62.8	27.2	0.32	2.86	1
02336150	2.56	5.29	5.06	25.8	24.1	1.00	5.30	1
02336180	4.57	11.00	9.03	19.0	25.9	2.07	8.10	1
02336200	1.01	0.98	1.47	94.5	32.3	0.15	1.77	1
02336238	0.68	0.92	1.60	106.0	33.6	0.16	1.67	1
02336325	0.96	1.35	2.14	53.8	42.0	0.29	2.33	1
02336690	0.81	0.52	1.22	90.7	20.3	0.13	1.31	1
02336697	0.52	0.21	1.09	136.0	19.0	0.09	0.77	1
02336700	0.76	0.79	1.46	75.8	28.3	0.17	1.67	1
02336705	2.48	8.80	4.95	33.7	29.5	0.85	6.43	1
02337081	0.78	0.88	1.43	86.9	28.6	0.15	1.71	1
Augusta								
02196570	1.19	0.66	1.67	96.0	19.9	0.17	1.45	2
02196605	0.70	1.67	1.86	117.0	28.1	0.17	2.19	2
02196725	1.91	1.44	2.67	118.0	42.4	0.25	3.63	3
02196730	2.26	4.06	3.97	80.6	33.4	0.42	6.37	3
02196760	0.70	1.56	2.07	111.0	23.0	0.20	3.82	3
02196850	0.44	0.30	1.06	239.0	28.5	0.07	0.81	2
Columbus								
02341542	5.22	6.54	4.96	36.8	1.0	0.82	5.46	2
02341544	0.88	1.58	2.20	69.7	17.6	0.26	2.38	2
02341546	0.58	0.26	1.06	81.8	16.0	0.12	0.95	2
02341548	0.74	1.42	2.23	60.5	16.8	0.29	2.33	2

Table 2. Selected basin characteristics for statewide urban lagtime study sites, by city—Continued

[t_L, lagtime in hours; DA, drainage area, in square miles; L, channel length, in miles; S, main channel slope, in feet per mile; TIA, area that is impervious to infiltration of rainfall, in percent; $L/(S)^{0.5}$, a ratio where L and S have been previously defined; RT_L, rural lagtime, in hours, for an equivalent rural drainage basin in the same hydrologic area as the urban basin (Inman, 1986); R, flood-frequency region where the basin is located (Stamey and Hess, 1993)]

Station number	Basin characteristics							
	T_L	DA	L	S	TIA	$L/(S)^{0.5}$	RT_L	R
Moultrie								
02318565	0.60	0.27	0.80	60.3	23.2	0.10	2.17	4
02327202	0.76	0.48	1.02	45.6	33.9	0.15	3.04	4
02327203	0.53	0.39	0.74	48.7	21.0	0.11	2.72	4
02327204	1.41	1.65	2.10	25.4	22.3	0.42	6.19	4
Rome								
02395990	0.48	0.37	0.82	76.4	16.6	0.08	1.15	1
02396290	0.88	0.62	0.97	98.6	6.6	0.10	1.40	1
02396510	0.23	0.04	0.34	772.0	17.4	0.01	0.24	1
02396515	0.48	0.29	0.72	257.0	18.3	0.06	0.79	1
02396550	0.29	0.19	0.70	345.0	18.8	0.04	0.60	1
02396680	1.20	1.31	2.41	55.2	22.1	0.32	2.28	1
Savannah								
02203541	0.77	0.24	0.84	17.5	59.5	0.20	3.03	3
02203542	2.40	1.27	2.02	13.6	19.5	0.55	6.71	3
02203543	1.46	0.95	1.78	13.0	29.7	0.49	6.01	3
02203544	0.58	0.18	0.51	29.9	25.9	0.09	2.27	3
Thomasville								
02326182	0.41	0.12	0.46	89.7	16.4	0.05	1.36	4
02327467	1.27	1.07	1.65	31.5	20.9	0.29	4.81	4
02327468	1.72	2.90	3.05	24.9	25.6	0.61	7.94	4
02327471	0.42	0.21	0.60	82.2	42.4	0.07	1.77	4
02327473	0.78	1.04	1.21	60.6	26.6	0.16	3.88	4
02327474	0.46	0.12	0.60	110.0	6.1	0.06	1.27	4
Tifton								
02317713	1.77	0.58	1.70	17.3	19.3	0.41	4.45	3
02317715	0.93	0.71	1.70	25.1	35.9	0.34	4.32	3
02317802	0.45	0.16	0.53	62.8	51.7	0.07	1.71	3
02317816	0.54	0.30	0.72	79.6	46.8	0.08	2.09	3
Valdosta								
02317564	1.91	1.27	1.70	11.8	22.3	0.49	7.01	3
02317566	3.02	3.81	3.69	9.4	20.4	1.20	12.1	3
023177551	0.57	0.16	0.74	23.4	20.7	0.15	2.33	4
023177553	1.46	0.99	1.52	26.3	28.7	0.30	4.91	4
023177554	1.15	2.66	3.03	19.4	29.8	0.69	8.26	4
023177556	0.36	0.16	0.49	40.8	11.8	0.08	1.96	4
023177557	0.63	0.55	0.89	47.9	27.1	0.13	3.17	4
023177558	0.94	1.18	1.52	41.2	34.4	0.24	4.61	4

12 percent is due to other factors. The standard error of regression (or estimate) is, by definition, one standard deviation on each side of the regression line and contains about two-thirds of the data within this range. The standard error of prediction defines the error to be expected at ungaged sites about two-thirds of the time. A summary of the lagtime equations and their related statistics is given in table 3.

Table 3. Equations for estimating lagtime for urban streams in Georgia

[T_L, lagtime for urban streams, in hours; DA, drainage area, in square miles; TIA, area that is impervious to infiltration of rainfall, in percent; ±, plus or minus; S, slope, in feet per mile]

Regions 1, 2, 3 lagtime estimating equation (in hours)	Standard error of regression (in percent)	Coefficient of determination (R^2)	Standard error of prediction (in percent)
$T_L = 7.86DA^{0.35}TIA^{-0.22}S^{-0.31}$	±28.9	0.84	±29.7
Region 4 lagtime estimating equation (in hours)	**Standard error of regression (in percent)**	**Coefficient of determination (R^2)**	**Standard error of prediction (in percent)**
$T_L = 6.10DA^{0.35}TIA^{-0.22}S^{-0.31}$	±28.9	0.84	±29.7

Limits of Independent Variables

The effective usable range of basin characteristics for the region 1, 2, and 3 urban lagtime equation is as follows:

Variable	Minimum	Maximum	Units
DA	0.04	19.1	square miles
TIA	1.0	61.6	percent
S	9.4	772.0	feet per mile

The effective usable range of basin characteristics for the region 4 urban lagtime equation is as follows:

Variable	Minimum	Maximum	Units
DA	0.12	2.9	square miles
TIA	6.1	42.4	percent
S	19.4	110.0	feet per mile

TESTING OF URBAN LAGTIME REGRESSION EQUATIONS

The accuracy of the urban lagtime regression equations were evaluated using the same four tests used for the dimensionless hydrograph. The standard error of regression has been explained and presented in a previous section of this report. Discussions of verification, bias, and sensitivity are presented below.

Verification

Verification was conducted by computing the PRESS statistic using SAS (SAS Institute, Inc., 1989). The PRESS statistic, according to Myers (1986), is computed by setting aside the first observation of the data set and using the remaining n-1 observations to estimate the coefficients for the regression model. The first observation is then replaced and the second observation with held with coefficients estimated again. Each observation is removed sequentially, and the model is fit n times. The deleted observation is estimated each time, resulting in n prediction errors or PRESS residuals. The PRESS statistic is computed as the sum of the squares of these residuals. The PRESS residuals are true prediction errors because the residuals are independent of the equation used to estimate them. Thus, because the observations are not used simultaneously for model fit and model assessment, a true test of validation can be accomplished.

The standard error of prediction can be computed, as described by E.J. Gilroy (U.S. Geological Survey, written commun., 1988) from the PRESS statistic using the equation

$$SEP = (PRESS(\tau))^{0.5} \quad (1)$$

where
SEP is the standard error of prediction;
PRESS is the prediction sum of squares; and

$$\tau = \left(\frac{1}{n}\right)\left(\frac{n+p+1}{n+p}\right)\left(\frac{n-1}{n}\right)$$

where
n is the sample size; and
p is the number of parameters including the constant 5.

In the above equation, τ is a multiplier derived from n and p by which the PRESS statistic is multiplied. τ is a constant for a given set of equations with the same number of parameters and sample size.

The standard error of prediction is a measure of how accurately the regression equations estimate the dependent variable at other than calibration sites (Sauer and others, 1983). On the other hand, the standard error of regression, or estimate, obtained from the calibration phase, is a measure of how accurately the regression equations estimate the dependent variable at the sites used to calibrate them.

Bias

Two tests for bias were performed—one for variable bias and the other for geographical bias. The variable bias tests were conducted by plotting the residuals (difference between observed and predicted lagtimes) against each of the independent variables for all stations. The plots were visually inspected to determine whether there was a consistent over-prediction or underprediction within the range of any of the independent variables. These plots also verified the linearity assumptions of the equations. On the basis of visual inspection of the plots, the equations are free of variable bias throughout the range of independent variables.

Geographical bias was tested by determining the number of positive and negative residuals at sites in a city. Although some cities do have a majority of negative or positive residuals, the Wilcoxin Signed Ranks test, as described by Tasker (1982), when applied to the residuals in each of the 11 cities, indicates that the estimated lagtimes are not biased.

Sensitivity

The sensitivity of lagtime to errors in the three independent variables in the regression equations was analyzed. The computation of independent variables is subject to errors in measurement and judgment. To illustrate the effect of such errors, the equations were tested to determine how much error was introduced into the computed lagtime from specified percentage errors in the independent variables. The test results are shown in table 4. The table was computed by assuming that all independent variables were constant, except the one being tested for sensitivity.

Table 4. Sensitivity of computed lagtimes to errors in independent variables using the statewide lagtime equations

[DA, drainage area, in square miles; TIA, area that is impervious to infiltration of rainfall, in percent; and S, the main channel slope, in feet per mile]

Percent error in independent variable	Independent variables (Percent error in computed lagtime)		
	DA	TIA	S
+50	+16.3	-7.8	-13.2
+25	+8.5	-3.9	-7.0
+10	+3.9	-1.6	-3.1
-10	-3.1	+2.3	+3.9
-25	-9.3	+6.2	+10.1
-50	-21.7	+14.7	+26.4

APPLICATION OF TECHNIQUE

The following example illustrates the procedural steps included in computing a hydrograph and estimating lagtime at a site. For this example, a hydrograph with a 25-year recurrence interval is simulated for peak discharge at Conley Creek at Rock Cut Road near Forest Park, Ga. The procedures are as follows.

1. Locate the site on the best available topographic map and determine the drainage area and slope upstream from the highway crossing. At Rock Cut Road, the drainage area is 1.88 mi^2 and the slope is 74.1 feet per mile. Next, locate the site on the best available aerial photography and determine the TIA. In this case, TIA is 26.7 percent.
2. Using figure 1, determine the rural flood-frequency and lagtime region in which the site is located. For this example, the site (basin) is in region 2.
3. Using the most recent flood-frequency equation for region 2 (Inman, 1995), compute the peak discharge and estimate the lagtime from this report. For this example the computed 25-year peak discharge is 1,360 cubic feet per second, and the estimated lagtime is 1.25 hours.
4. Simulate a hydrograph using the statewide dimensionless hydrograph, the estimated 25-year peak discharge, and the estimated lagtime. For this example basin, the simulated hydrograph is illustrated in figure 3 and the data points are listed in table 5. It should be emphasized that this simulated hydrograph is a typical, or average, hydrograph that can be used for design purposes, and is not an actual storm hydrograph.

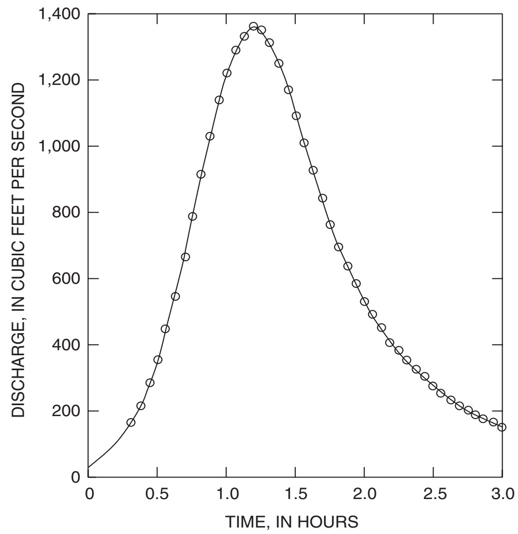

Figure 3. Simulated flood hydrograph for Conley Creek at Rock Cut Road near Forest Park, Georgia.

Table 5. Simulated coordinates of the flood hydrograph for Conley Creek at Rock Cut Road near Forest Park, Georgia

[t/T_L, time in hours divided by lagtime in hours; T_L, lagtime in hours; hr, hours; Q/Q_p, discharge in cubic feet per second divided by peak discharge in cubic feet per second; Q_p, peak discharge in cubic feet per second; ft^3/s, cubic feet per second]

t/T_L (from table 1)	T_L (hr)	$(t/T_L)T_L$=time (hr)	Q/Q_p (from table 1)	Q_p (ft^3/s)	$(Q/Q_p)Q_p$=discharge (ft^3/s)
0.25	1.25	0.31	0.12	1,360	163
.30	1.25	.38	.16	1,360	218
.35	1.25	.44	.21	1,360	286
.40	1.25	.50	.26	1,360	354
.45	1.25	.56	.33	1,360	449
.50	1.25	.62	.40	1,360	544
.55	1.25	.69	.49	1,360	666
.60	1.25	.75	.58	1,360	789
.65	1.25	.81	.67	1,360	911
.70	1.25	.88	.76	1,360	1,030
.75	1.25	.94	.84	1,360	1,140
.80	1.25	1.00	.90	1,360	1,220
.85	1.25	1.06	.95	1,360	1,290
.90	1.25	1.12	.98	1,360	1,330
.95	1.25	1.19	1.00	1,360	1,360
1.00	1.25	1.25	.99	1,360	1,350
1.05	1.25	1.31	.96	1,360	1,310
1.10	1.25	1.38	.92	1,360	1,250
1.15	1.25	1.44	.86	1,360	1,170
1.20	1.25	1.50	.80	1,360	1,090
1.25	1.25	1.56	.74	1,360	1,010
1.30	1.25	1.62	.68	1,360	925
1.35	1.25	1.69	.62	1,360	843
1.40	1.25	1.75	.56	1,360	762
1.45	1.25	1.81	.51	1,360	694
1.50	1.25	1.88	.47	1,360	639

Table 5. Simulated coordinates of the flood hydrograph for Conley Creek at Rock Cut Road near Forest Park, Georgia—Continued

[t/T_L, time in hours divided by lagtime in hours; T_L, lagtime in hours; hr, hours; Q/Q_p, discharge in cubic feet per second divided by peak discharge in cubic feet per second; Q_p, peak discharge in cubic feet per second; ft^3/s, cubic feet per second]

t/T_L (from table 1)	T_L (hr)	$(t/T_L)T_L$=time (hr)	Q/Q_p (from table 1)	Q_p (ft^3/s)	$(Q/Q_p)Q_p$=discharge (ft^3/s)
1.55	1.25	1.94	.43	1,360	585
1.60	1.25	2.00	.39	1,360	530
1.65	1.25	2.06	.36	1,360	490
1.70	1.25	2.12	.33	1,360	449
1.75	1.25	2.19	.30	1,360	408
1.80	1.25	2.25	.28	1,360	381
1.85	1.25	2.31	.26	1,360	354
1.90	1.25	2.38	.24	1,360	326
1.95	1.25	2.44	.22	1,360	299
2.00	1.25	2.50	.20	1,360	272
2.05	1.25	2.56	.19	1,360	258
2.10	1.25	2.62	.17	1,360	231
2.15	1.25	2.69	.16	1,360	218
2.20	1.25	2.75	.15	1,360	204
2.25	1.25	2.81	.14	1,360	190
2.30	1.25	2.88	.13	1,360	177
2.35	1.25	2.94	.12	1,360	163
2.40	1.25	3.00	.11	1,360	150

SUMMARY

Lagtime is one of the components needed to simulate a design flood hydrograph for an ungaged site. Estimating equations for lagtime in rural areas and for the Atlanta urban area were presented in a 1986 U.S. Geological Survey report; however, the applicability of these equations to urban areas other than the Atlanta metropolitan area was unknown. Therefore, a need existed for estimating lagtime for urban areas in other parts of Georgia. To address this need, multiple-regression analysis was used to define relations between lagtime and selected basin characteristics, of which drainage area, total impervious area, and main channel slope were significant at the 95-percent confidence limit for urban basins up to 25 square miles in Georgia. A qualitative variable was used to account for a geographical bias in region 4 in southwestern Georgia. A total of 329 floods at 69 gaging stations in 11 cities in Georgia were used in the analysis. These new lagtime equations supersede the equation published in 1986 for the Atlanta area.

The statewide lagtime equation was verified by computing the PRESS (Prediction Sum of Squares) statistic using SAS (the Statistical Analysis System). There was no variable bias in the statewide equation, and sensitivity tests indicated that drainage area was the most sensitive basin characteristic.

A simulated flood hydrograph can be computed by applying lagtime, obtained from the proper regression equation, and peak discharge of a specific recurrence interval, to the dimensionless hydrograph published in 1986. The coordinates of a runoff hydrograph can be computed by multiplying lagtime by the time ratios and peak discharge by the discharge ratios of the dimensionless hydrograph. The simulated hydrograph is a typical, or average, hydrograph that can be used for design purposes, and should not be confused with an actual storm hydrograph.

REFERENCES CITED

Becker, L.D., 1990, Simulation of flood hydrographs for small basins in Missouri: U.S. Geological Survey Water-Resources Investigations Report 90-4045, 40 p.

Cochran, W.G., 1963, Sampling techniques: New York, John Wiley, 413 p.

Inman, E.J., 1986, Simulation of flood hydrographs for Georgia streams: U.S. Geological Survey Water-Resources Investigations Report 86-4004, 41 p.

———1995, Flood-frequency relations for urban streams in Georgia—1994 update: U.S. Geological Survey Water-Resources Investigations Report 95-4017, 27 p.

Mason, R.R., and Bales, J.D., 1996, Estimating flood hydrographs for urban basins in North Carolina: U.S. Geological Survey Water-Resources Investigations Report 96-4085, 19 p.

Myers, R.H., 1986, Classical and modern regression with applications: Boston, Duxbury Press, 359 p.

Neely, B.L., 1989, Estimating flood hydrographs for Arkansas streams: U.S. Geological Survey Water-Resources Investigations Report 89-4109, 19 p.

O'Donnell, Terrance, 1960, Instantaneous unit hydrograph derivation by harmonic analysis: Commission of Surface Waters, Publication 51 International Association of Scientific Hydrology, 557 p.

Olin, D.A., and Atkins, J.B., 1988, Estimating flood hydrographs and volumes for Alabama streams: U.S. Geological Survey Water-Resources Investigations Report 88-4041, 25 p.

Riggs, H.C., 1968, Some statistical tools in hydrology: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A1, 39 p.

Robbins, C.H., 1986, Techniques for simulating flood hydrographs and estimating flood volumes for ungaged basins in central Tennessee: U.S. Geological Survey Water-Resources Investigations Report 86-4192, 32 p.

SAS Institute, Inc., 1989, SAS user's guide: Statistics, 583 p.

Sauer, V.B., Thomas, W.O., Stricker, V.A., and Wilson, K.V., 1983, Flood characteristics of urban watersheds in the United States: U.S. Geological Survey Water-Supply Paper 2207, 63 p.

Schneider, V.R., and Wilson, K.V., 1980, Hydraulic design of bridges with risk analysis: Federal Highway Administration, TS-80-226, 142 p.

Sherwood, J.M., 1993, Estimation of flood volumes and simulation of flood hydrographs for ungaged small rural streams in Ohio: U.S. Geological Survey Water-Resources Investigations Report 93-4080, 52 p.

Stamey, T.C., and Hess, G.W., 1993, Techniques for estimating magnitude and frequency of floods in rural basins of Georgia: U.S. Geological Survey Water-Resources Investigations Report 93-4016, 75 p.

Tasker, G.D., 1982, Simplified testing of hydrologic regression regions, *in* Proceedings of American Society of Civil Engineers, v. 108, p. 1218–1222.