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FINAL REPORT

FLOOD FREQUENCY RELATIONSHIPS FOR SMALL WATERSHEDS IN KANSAS

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16 Abstract

This report presents some new flood-frequency equations for Kansas that combine the best features of the Rational method and traditional regression equations. These equations provide estimates of discharges with recurrence intervals of 2, 5, 10, 25, 50 and 100 years for unregulated rural streams with drainage areas under 30 mi^2. The inputs to these equations are the drainage area, the mean annual precipitation, and rainfall intensity. The rainfall intensity is the average intensity over the drainage area for a duration equal to the watershed's time of concentration and the same recurrence interval as the desired discharge. Two sets of equations are presented. The equations in the first set are termed Extended Rational equations because the discharge is directly proportional to both rainfall intensity and drainage area, as in the Rational formula. The equations in the second set are power-type equations developed by traditional multiple-regression analysis. The two sets of equations are quite similar, with nearly identical standard errors.

Both sets of equations were developed from data for 72 USGS stream-flow gaging stations on unregulated rural streams with drainage areas under 30 mi2 and record lengths of 20 years or longer. Two-year through 100-year discharges for each station were computed from the annual peak-flow data by the most recent USGS method for Kansas. The time of concentration for each watershed was estimated from the channel length and average channel slope with the KDOT-KU equation for rural watersheds in Kansas. Point-rainfall intensities for these times of concentration were interpolated from KDOT's rainfall tables. Corresponding area-average rainfall intensities were determined from the precipitation depth-area-duration relationship in the U.S. Weather Bureau's Technical Paper No. 40. The runoff coefficient (C) for each recurrence interval was backed out from the Rational formula (Q = C i A) using the discharge from the frequency analysis, the area-average rainfall intensity and the drainage area. Predictive equations for the 2-year through 100-year runoff coefficients were developed by regression analysis. Many physical and climatic characteristics of the watershed were considered as possible explanatory variables. The recommended equations relate the runoff coefficients to mean annual precipitation (MAP). Maps illustrate the geographic variation in C, as predicted from MAP, across Kansas for the six recurrence intervals. The Extended Rational equations for the 2-year through 100-year discharges were obtained by substituting the recommended equations for C into the Rational formula. The report includes step-by-step instructions for applying the new equations and an example application.

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A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
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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

This report presents some new flood-frequency equations for Kansas that combine the best features of the rational method and traditional regression equations. These equations provide estimates of discharges with recurrence intervals of 2, 5, 10, 25, 50 and 100 years for unregulated rural streams with drainage areas under 30 mi^2. The inputs to these equations are the drainage area, the mean annual precipitation, and rainfall intensity. The rainfall intensity is the average intensity over the drainage area for a duration equal to the watershed's time of concentration and the same recurrence interval as the desired discharge. Two sets of equations are presented. The equations in the first set are termed Extended Rational equations because the discharge is directly proportional to both rainfall intensity and drainage area, as in the Rational formula. The equations in the second set are power-type equations developed by traditional multiple-regression analysis. The two sets of equations are quite similar, with nearly identical standard errors.

Both sets of equations were developed from data for 72 USGS stream-flow gaging stations on unregulated rural streams with drainage areas under 30 mi^2 and record lengths of 20 years or longer. Two-year through 100-year discharges for each station were computed from the annual peak-flow data by the most recent USGS method for Kansas. The time of concentration for each watershed was estimated from the channel length and average channel slope with the KDOT-KU equation for rural watersheds in Kansas. Point-rainfall intensities for these times of concentration were interpolated from KDOT's rainfall tables. Corresponding area-average rainfall intensities were determined from the precipitation depth-area-duration relationship in the

U.S. Weather Bureau's Technical Paper No. 40. The runoff coefficient (C) for each recurrence interval was backed out from the Rational formula (Q = C i A) using the discharge from the frequency analysis, the area-average rainfall intensity and the drainage area. Predictive equations for the 2-year through 100-year runoff coefficients were developed by regression analysis. Many physical and climatic characteristics of the watershed were considered as possible explanatory variables. The recommended equations relate the runoff coefficients to mean annual precipitation (MAP). Maps illustrate the geographic variation in C, as predicted from MAP, across Kansas for the six recurrence intervals. The Extended Rational equations for the 2-year through 100-year discharges were obtained by substituting the recommended equations for C into the Rational formula. The report includes step-by-step instructions for applying the new equations and an example application.

The flood frequency equations presented in the report exhibit lower standard errors than the USGS regression-based equations and thus should be more accurate. The equations also exhibit lower bias, particularly in western Kansas, and will probably yield smaller peak flow estimates in that area of the state. These equations are for unregulated rural streams with a contributing drainage area greater than 1.0 mi2 but less than 30 mi2 in Kansas. They may be used as a check or comparison of the USGS regression equations for bridge-sized structures. For road-sized culverts (less than 20 ft span) the equations should be used in lieu of the USGS regression equations. The peak flow should be determined by both the Extended Rational equations (Table 3.9) and the Three-variable regression equations (Table 3.14) and the larger discharge used for design. The Rational method should be used to determine peak flow for drainage areas less than 1 mi2.

ACKNOWLEDGMENTS

This project was supported by the Kansas Department of Transportation (KDOT) through the Kansas Transportation Research and New Developments (K-TRAN) Program. James R. Richardson, P.E., of KDOT served as project monitor. The authors sincerely appreciate the support of KDOT and the contributions of Mr. Richardson.

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CHAPTER 1 - INTRODUCTION

1.1 Flood Discharges for Bridges & Culverts

The design of bridges and culverts requires the estimation of flood discharges with specific recurrence intervals. Design discharges for small drainage structures are usually estimated by the Rational method. Design discharges for larger structures are most often estimated by regional regression equations developed by the U. S. Geological Survey (USGS) or others. KDOT's current guidelines recommend the Rational method for rural watersheds up to 640 acres and urban watersheds up to 1000 acres. KDOT recommends the current USGS regression equations for Kansas (Rasmussen and Perry, 2000) for rural watersheds larger than 640 acres. Both methods are limited to unregulated streams.

1.2 Rational Method

The Rational method for calculation of design discharges was first described by Irish engineer Thomas Mulvany in 1851 (Dooge, 1957). The method was introduced to the United States by Kuichling in 1889 (Kuichling, 1889), but it was not widely adopted by highway engineers until much later, probably due to inadequate guidance for estimation of the runoff coefficient, time of concentration and rainfall intensity. Johns Hopkins University's Storm Drainage Research Project, initiated in 1949, demonstrated the validity of the Rational method for estimation of flood discharges with specific recurrence intervals (Schaake and others, 1967). The major shortcoming of the method remains the lack of reliable guidance for estimation of runoff coefficients and the times of concentration, particularly for rural watersheds. Stated limits on the applicability of the method also vary widely. Its applicability to small urban watersheds is generally accepted. The method is also valid for larger urban watersheds and rural watersheds, but more research is needed to guide the selection of runoff coefficients for these conditions.

The Rational formula in its modern, frequency-based form can be stated as

$$Q(T) = k \cdot C(T) \cdot I(t_c,T) \cdot A \qquad (1.1)$$

in which

$Q(T)$ = discharge with recurrence interval T

k = units-conversion constant, which depends on units of other terms

$C(T)$ = runoff coefficient for recurrence interval T (dimensionless)

$I(t_c,T)$ = rainfall intensity for duration t_c and recurrence interval T

t_c = time of concentration for watershed

A = drainage area

The runoff coefficient, C(T), is an empirical coefficient that relates the T-year discharge per unit drainage area to the T-year rainfall intensity for duration t_c. It does not represent the fraction of the rainfall volume that runs off. The runoff coefficient accounts for the many factors other than rainfall intensity and drainage area that affect the discharge for recurrence interval T. Its value can exceed unity.

1.3 USGS Regression Equations for Kansas

The first regional flood-frequency equations applicable to small watersheds in Kansas were published by the USGS in 1975. These equations were updated in 1987 and again in 2000 to incorporate new data. The latest update, published in 2000, provides two sets of statewide flood-frequency equations: one for drainage areas over 30 mi^2 and another for drainage areas under 30 mi^2. The equations for drainage areas over 30 mi^2 have four inputs: drainage area, mean annual precipitation, channel slope and generalized soil permeability. The equations for drainage areas under 30 mi^2 have only two inputs: drainage area and mean annual precipitation. The equations for the small watersheds have much larger standard errors than the equations for large watersheds.

1.4 Overview of Research

This report presents an analysis of peak-flow records for USGS streamflow-gaging stations in Kansas with drainage areas under 30 mi^2. This analysis leads to some new equations for design discharges that combine the best features of the Rational method and traditional regression equations.

CHAPTER 2 - DATA FOR REGIONAL REGRESSION ANALYSES

2.1 Selection of USGS Streamflow-Gaging Records

Our data set included 72 USGS streamflow-gaging stations in Kansas that met the following conditions:

- Drainage area under 30 mi^2
- Record length of 20 years or more (through water year 2004)
- Unregulated stream
- Rural watershed
- Well-defined watershed boundary; no apparent non-contributing areas

The USGS database includes 83 stations that meet the first three criteria. We excluded nine of these stations from our data set because of indeterminate watershed boundaries and apparent non-contributing areas. Station 6893300, Indian Creek at Overland Park, was excluded because its watershed is largely urban. Station 06879650, King's Creek near Manhattan, was excluded because our frequency analysis of the peak-flow record yielded an unreasonably large 100-year discharge results, indicating a likely error in the station's rating curve. Table A.1 lists the ID numbers, names, drainage areas and record lengths for the 72 stations. Figure 2.1 shows the locations of these stations.

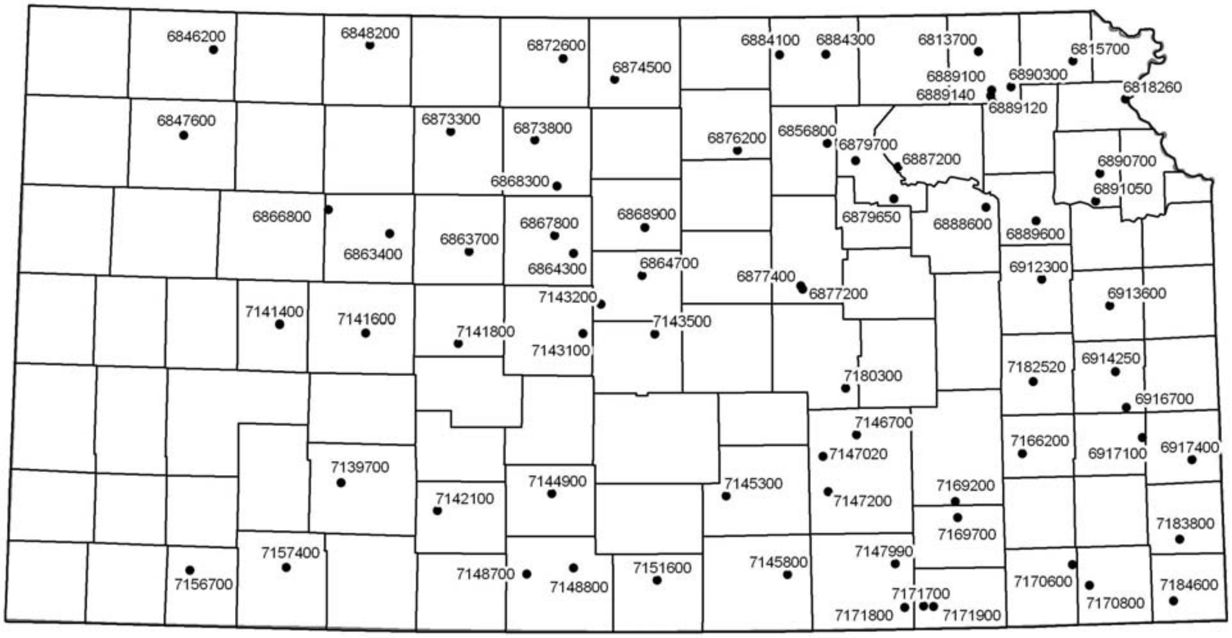

Figure 2.1: Locations of selected USGS streamflow-gaging stations

2.2 Flood Discharges

We performed a flood-frequency analysis for each station by the standard Federal procedures (U. S. Interagency Advisory Committee on Water Data, 1981) with the USGS's PEAKFQ program. The generalized skew coefficient for each station was obtained from a regression equation for Kansas (Rasmussen and Perry, 2000) rather than the nationwide map. Table A.2 lists the resulting discharges for recurrence intervals of 2, 5, 10, 25, 50 and 100 years

As a quality-control measure, the 100-year discharges computed from the station records were plotted on the USGS's graph of maximum observed discharges vs. drainage area for Kansas (Rasmussen and Perry, 2000). The 100-year discharge for station 6879650, Kings Creek near Manhattan, plotted far above the envelope curve for

Eastern Kansas, which indicated a likely problem with the station's rating curve at flood stages. We excluded this station from our data set for the regression analyses.

2.3 Rational Runoff Coefficients

We computed Rational runoff coefficients for the six recurrence intervals for each station with the Rational formula, rearranged as

$$C(T) = \frac{Q(T)}{645.3\ I_a(t_c, T) \cdot A} \tag{2.1}$$

for $Q(T)$ in cfs, $I_a(t_c,T)$ in in./hr and A in mi^2.

Times of concentration were computed with the KU-KDOT equation for rural watersheds in Kansas (McEnroe and Zhao, 1999):

$$t_c = 0.176\left(\frac{L}{\sqrt{Sl}}\right)^{0.66} \tag{2.2}$$

in which

t_c = time of concentration (hr)

L = length of main channel, extended to the drainage divide (mi)

Sl = average slope of main channel (ft/ft)

The average slope of the main channel is defined as 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).

Drainage areas, channel lengths and average channel slopes were determined from scanned USGS 1:24,000 topographic maps. These digital maps, obtained from the State of Kansas's Data Access and Support Center (DASC), were imported into ArcGIS with the Lambert Conformal Conic map projection. Watershed boundaries were delineated manually within ArcGIS. Most of this work was done as part of a previous K-

TRAN research project (McEnroe and Gonzalez, 2003). The drainage areas are listed in Table A.3. The channel lengths, average channel slopes and times of concentrations are listed in Table A.4. The drainage areas range from 0.17 mi^2 to 29.6 mi^2, and the times of concentration range from 0.6 hr to 11.1 hr.

Point-rainfall intensities for the required durations and recurrence intervals were obtained from KDOT's Rainfall Tables for Counties in Kansas. The KDOT rainfall tables were developed from the rainfall frequency maps in the U. S. Weather Bureau's Technical Paper 40, "Rainfall Frequency Atlas of the United States" (Hershfield, 1961), and National Weather Service's Technical Memorandum NWS HYDRO-35, "Five- to 60-Minute Precipitation Frequency for the Eastern and Central United States," (Frederick, et al., 1977).

When the Rational formula is applied to a watershed larger than a few hundred acres, the relevant rainfall intensity is the basin-average rainfall intensity, rather than the point-rainfall intensity, for a duration equal to the time of concentration. The ratio of basin-average rainfall intensity to point-rainfall intensity for the same duration and recurrence interval depends on the duration and the drainage area. This relationship is described by the equation

$$I_a(D,T) = I_p(D,T)\left[1 - BV\left(1 - e^{-0.015A}\right)\right] \tag{2.3}$$

in which

$I_a(D,T)$ = basin-average rainfall intensity for duration D and recurrence interval T

$I_p(D,T)$ = point rainfall intensity for duration D and recurrence interval T

A = drainage area (mi^2)

BV = coefficient that varies with duration as shown in Table 2.1

Table 2.1: BV factor in Eq. 2.3.

Duration (hours)	BV
0.5	0.48
1	0.35
3	0.22
6	0.17
24	0.09

The U. S. Army Corps of Engineers fitted Eq. 2.3 and the coefficients in Table 2.1 to a graphical relationship developed by the U. S. Weather Bureau (USACE, 1998; USWB, 1958). The paired values in Table 2.1 are plotted in Figure 2.2. We fitted this relationship with the equation

$$BV = 0.355\, D^{-0.428} \tag{2.4}$$

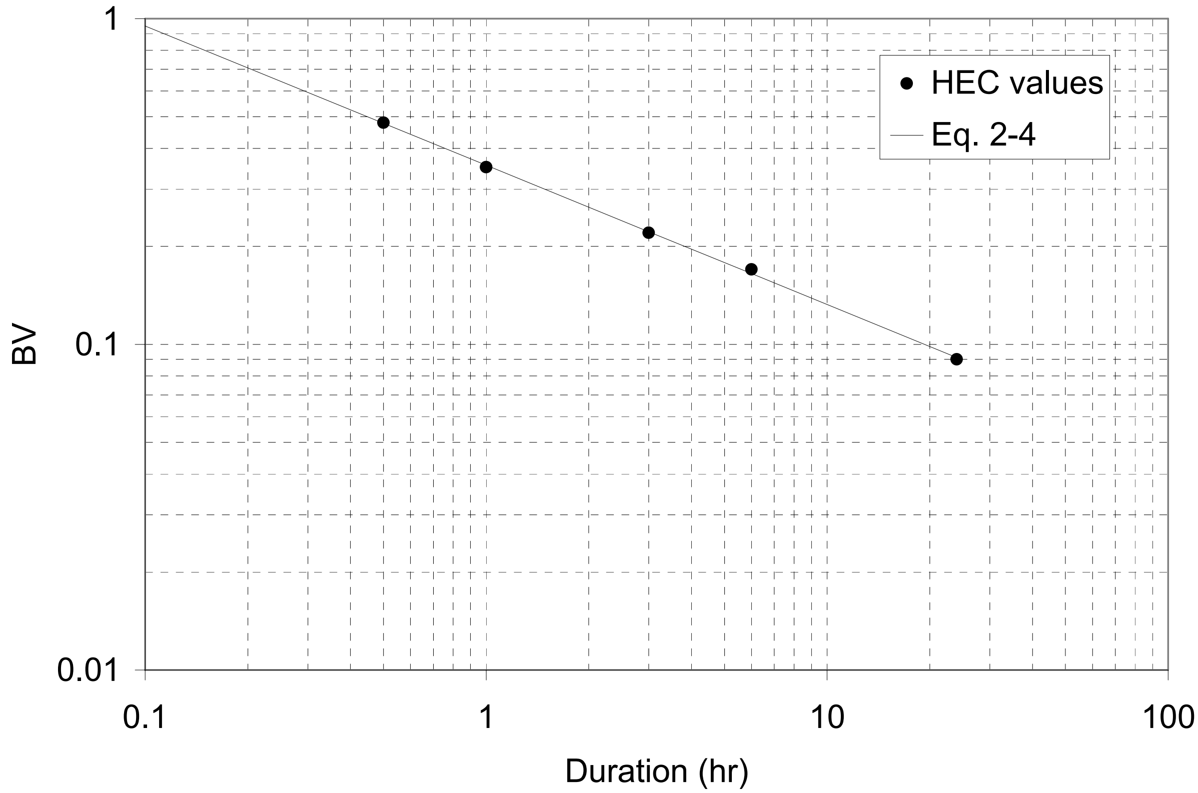

Figure 2.2: Relationship between BV in Eq. 2.3 and drainage area

Substituting Eq. 2.4 for BV and t_c for D in Eq. 2.3 yields

$$I_a(t_c, T) = I_p(t_c, T)\left[1 - \left(0.355\, t_c^{-0.428}\right)\left(1 - e^{-0.015\,A}\right)\right] \qquad (2.5)$$

We computed the basin-average rainfall intensities for each watershed and recurrence interval with Eq. 2.5.

Table A.3 lists the runoff coefficients computed with Eq. 2.1 for the 72 gaged watersheds and the six recurrence intervals.

2.4 Possible Explanatory Variables

The magnitude of the T-year flood depends on the physical and climatic characteristics of the watershed. The most important physical characteristic is the drainage area, and the most relevant rainfall characteristic is the T-year rainfall intensity (or the corresponding depth) for a duration equal to the time of concentration. The Rational formula accounts directly for both of these variables. Other relevant physical characteristics include channel length and slope, vegetation/land cover, and soil/geologic properties. The Rational method accounts for the channel length and slope through the time of concentration. Relevant climatic characteristics include mean annual precipitation and mean annual potential evapotranspiration.

The variables listed below were included as possible explanatory variables in the regression analyses for the flood discharges and runoff coefficients. The first three variables are explained in section 2.3; the others are explained in sections 2.4.1 through 2.4.6. Tables A.4 and A.5 list the values of these variables for the 72 gaged watersheds.

A = drainage area, A (mi^2)

$I(t_c,T)$ = basin-average rainfall intensity for recurrence interval T and duration t_c (hr)

Sl = average slope of main channel

Sh = basin shape factor (dimensionless)

SP = generalized soil permeability (in./hr)

CN = NRCS runoff curve number

MAP = mean annual precipitation (in.)

MAE = mean annual lake evaporation (in.)

MAD = mean annual precipitation deficit (in.)

2.4.1 Basin Shape Factor

A watershed with a compact shape will experience larger flood peaks than an elongated watershed with the same drainage area. The basin shape factor, Sh, is a dimensionless measure of watershed shape. It is defined as

$$Sh = \frac{L^2}{A} \tag{2.6}$$

A larger value of Sh indicates a more elongated basin shape. The Sh values for the 72 gaged selected watersheds range from 1.9 to 19 with a median value of 4.6.

2.4.2 Soil Permeability

A generalized soil permeability for each watershed was obtained from the STATSGO database of the U. S. Department of Agriculture (USDA, 1994). This generalized soil permeability, SP, represents a typical infiltration rate for saturated soil. It is the same soil permeability used in the current USGS regression equations for

Kansas (Rasmussen and Perry, 2000). The SP values for the selected watersheds range from 0.3 to 3.0 in./hr with a median value of 0.9 in./hr.

2.4.3 Runoff Curve Number

The NRCS runoff curve number accounts for the combined effects of soils, vegetation, land use and antecedent soil moisture on the rainfall-runoff relationship. The runoff curve number is determined by three factors: the type of land cover, the hydrologic soil group (HSG) classification of the soil, and the antecedent moisture condition (AMC) classification. The NRCS has defined four hydrologic soil groups: A, B, C, and D. The HSG classifications indicate runoff-producing potential, based on the soil's permeability and moisture storage capacity. Runoff-producing potential is lowest for group A soils and highest for group D soils. The NRCS has defined three antecedent moisture conditions: AMC I, II and III. AMC II represents an average condition, AMC I is an unusually dry condition, and AMC III is an unusually wet condition. Table 2.2 lists curve numbers for AMC II for all possible combinations of the four hydrologic soil types and 19 aggregated land uses for the watersheds. The table was developed previously by McEnroe and Gonzalez (2003) from similar tables published by the NRCS.

Table 2.2: Runoff curve numbers for average antecedent moisture condition (AMC II)

Land Cover	Hydrologic Soil Group			
	A	B	C	D
Open Water	100	100	100	100
Low Intensity Residential	57	72	81	86
High Intensity Residential	61	75	83	87
Commercial / Industrial / Transportation	89	92	94	95
Bare Rock / Sand / Clay	77	86	91	94
Quarries / Strip Mine / Gravel Pits	77	86	91	94
Transitional	43	65	76	82
Deciduous Forest	36	60	73	79
Evergreen Forest	36	60	73	79
Mixed Forest	36	60	73	79
Shrubland	35	56	70	77
Grasslands / Herbaceous	49	69	79	84
Pasture / Hay	49	69	79	84
Row Crops	67	78	85	89
Small Grains	63	75	83	87
Fallow	76	85	90	93
Urban / Recreational Grasses	39	61	74	80
Woody Wetlands	36	60	73	79
Emergent Herbaceous Wetlands	49	69	79	84

Hydrologic soil group classifications for the soils in the selected watersheds were determined from the Detailed Soils 24K digital data set of the NRCS. The Soil Survey Geographic (SSURGO) dataset, the certified version of the Detailed Soils 24K data set, was used where available. The State Soil Geographic (STATSGO) data set of the NRCS was used as a visual aid to understand the general distribution of soil types in Kansas. These data sets were provided by the Kansas Data Access and Support Center (DASC).

Figure 2.3 shows the general distribution of hydrologic soil groups in Kansas. This map was developed from the STATSGO data set. All four hydrologic soil groups are present in Kansas. Soil groups C and D are predominant in Eastern Kansas. Soil group B is predominant in Western Kansas. Soil group A occurs mainly in the Arkansas River lowlands.

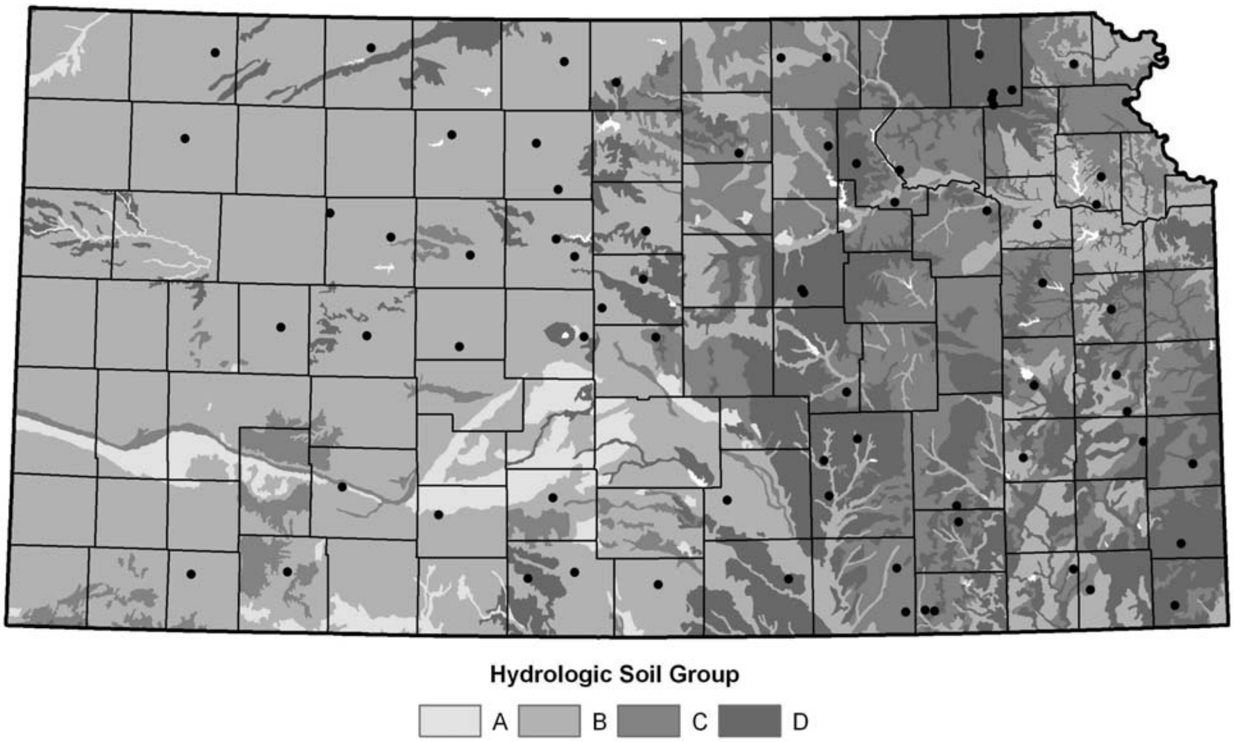

Figure 2.3: NRCS hydrologic soil groups

Land-cover data for the selected watersheds were obtained from the National Land Cover Data 1992 (NLCD 92) digital data set of the USGS. The USGS developed this data set, which depicts 21 land-cover classes, from early- to mid-1990s Landsat Thematic Mapper satellite data and a variety of supporting information. The digital land-cover map was clipped with the watershed boundaries coverage to obtain the land-cover data for the selected watersheds,

A combined soils-land cover map was created by overlaying the final soils map on the final land-cover map. A runoff curve number was assigned to each combination of hydrologic soil group and land-cover class according to Table 2.2. The curve number for each watershed was calculated as an area-weighted average of the curve numbers for the soils-land cover units within the watershed. The runoff curve numbers for the selected watersheds range from 72 to 85 with a median value of 78.

2.4.4 Mean Annual Precipitation

The mean annual precipitation (MAP) for each watershed was interpolated from the map in Figure 2.4, developed by the USGS (Rasmussen and Perry, 2000). MAP values for the selected watersheds range from 19.1 to 42.6 inches.

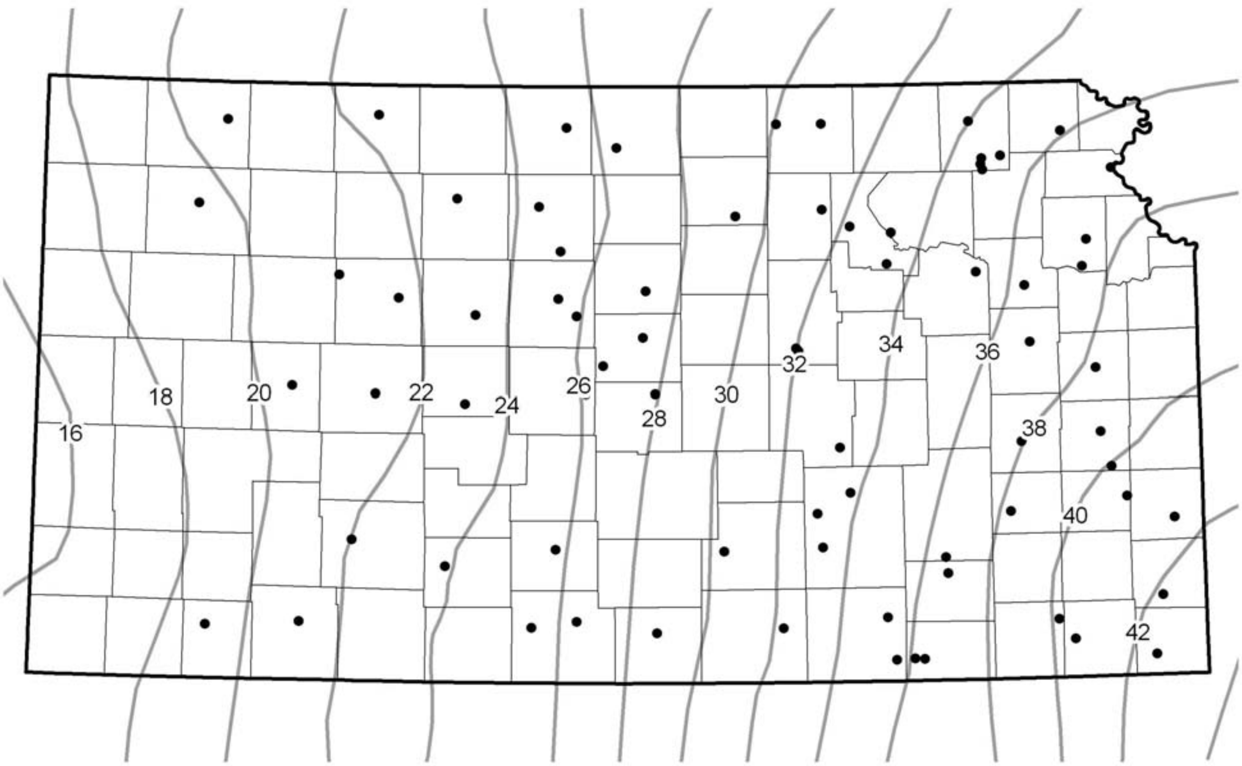

Figure 2.4: Mean annual precipitation (inches)

2.4.5 Mean Annual Lake Evaporation

The mean annual lake evaporation (MAE) for each watershed was interpolated from the map in Figure 2.5, developed by the National Weather Service (Farnsworth and others, 1982). Lake evaporation is a good approximation for potential evapotranspiration. MAE values for the selected watersheds range from 43.5 to 68.9 inches.

2.4.6 Mean Annual Precipitation Deficit

The mean annual precipitation deficit (MAD) is defined as the difference between mean annual lake evaporation and mean annual precipitation. MAD is a general indicator of normal soil-moisture conditions; a larger MAD value indicates drier soils. Figure 2.6 shows the distribution of MAD across Kansas. MAD values for the selected watersheds range from 2.8 to 49.6 inches.

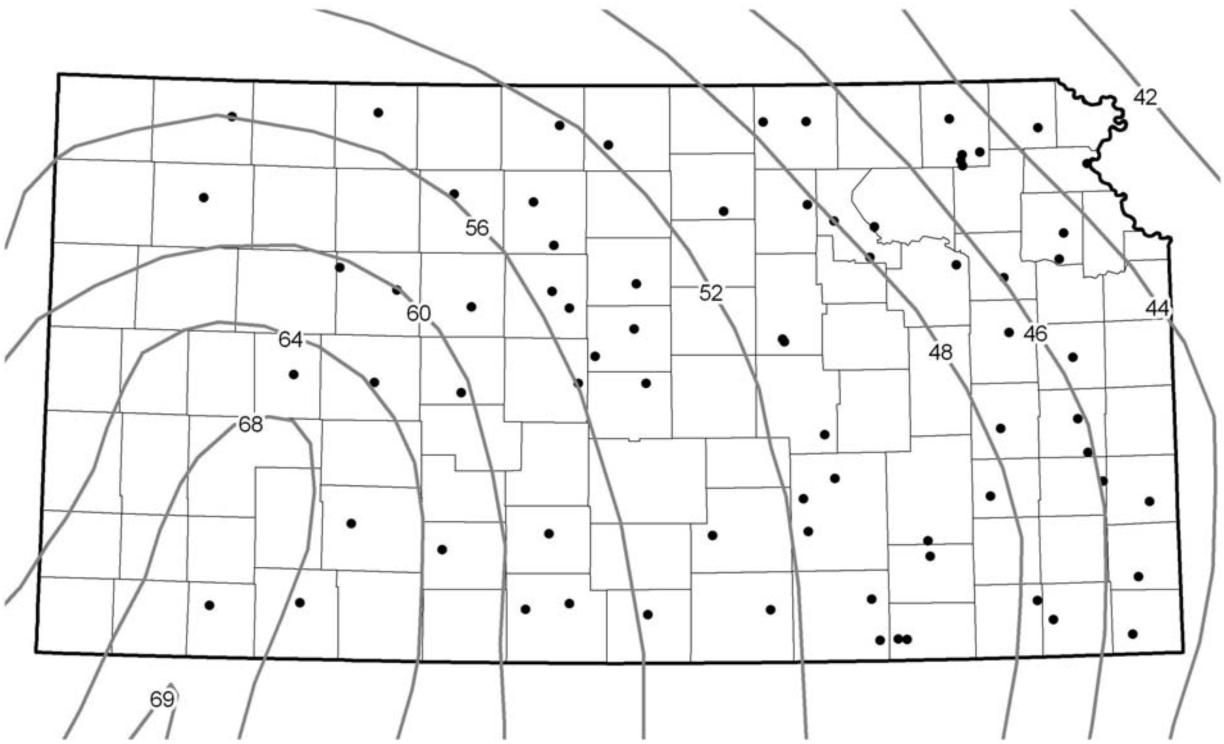

Figure 2.5: Mean annual lake evaporation (inches)

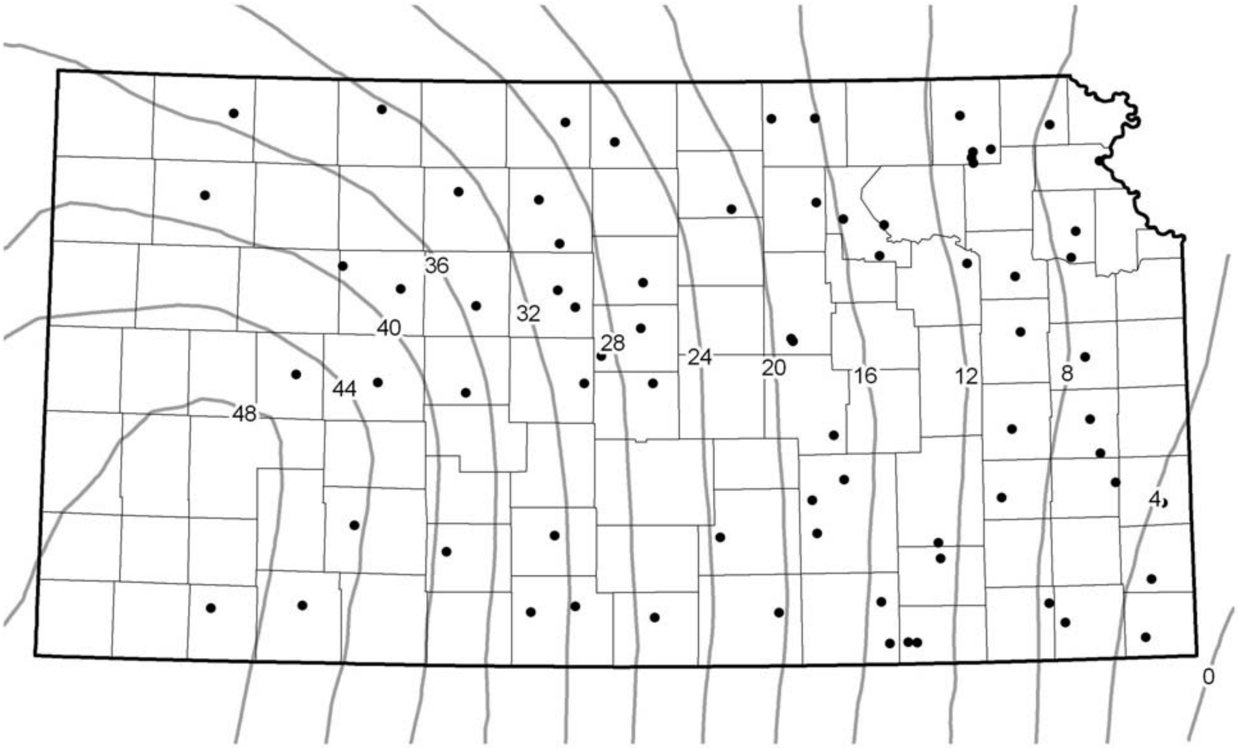

Figure 2.6: Mean annual precipitation deficit (inches)

CHAPTER 3 - REGIONAL REGRESSION ANALYSES

3.1 Rational Runoff Coefficients

Our regression analyses for the runoff coefficients began with examination of the correlation matrices for the runoff coefficients and possible explanatory variables for recurrence intervals of 2, 25 and 100 years, shown in Tables 3.1 through 3.3. The correlation coefficients indicate that the three climatic variables (MAP, MAD and MAE) have the greatest influence on the runoff coefficients. However, scatter plots of C versus these three variables exhibit heteroscedasticity, i.e., the scatter in C increases as the value of the predictor variable increases, as shown in Figure 3.1 for C25 versus MAP. The relationships between the logarithms of the runoff coefficients and these predictor variables are more nearly homoscedastic (variance in dependent variable constant over range of independent variable), as shown in Figure 3.2 for the logarithms of C25 and MAP. For this reason, the linear regression analyses were performed on the base-10 logarithms of the variables, resulting in equations of the form

$$\log Y = a + b_1 \log X_1 + b_2 \log X_2 + \ldots + b_n \log X_n \qquad (3.1)$$

in which

Y = dependent variable

X_i = independent variables

a = regression constant (intercept)

b_i = regression coefficients on independent variable

An inverse logarithmic transformation Eq. 3.1 results in a power-type equation for the dependent variable:

$$Y = 10^{a} (X_1)^{b_1} (X_2)^{b_2} ... (X_n)^{b_n} \quad (3.2)$$

Tables 3.4 through 3.6 show the correlation matrices for the logarithms of the runoff coefficients and possible explanatory variables for recurrence intervals of 2, 25 and 100 years. The runoff coefficients are correlated most strongly with the three climatic variables, which are highly collinear. The C values are also moderately correlated with soil permeability and runoff curve number and weakly correlated with basin shape factor. These correlation coefficients generally decrease with increasing recurrence interval. The runoff coefficients exhibit negligible correlation with drainage area, rainfall intensity and channel slope because the other terms in the Rational formula account for their effects on flood discharge.

Table 3.1: Correlation matrix for C2 and possible explanatory variables

	C2	A	Sh	Sl	SP	CN	$I2_a$	MAP	MAE	MAD
C2	1.00									
A	0.05	1.00								
Sh	-0.36	0.41	1.00							
Sl	-0.15	-0.50	-0.42	1.00						
SP	-0.43	-0.01	0.14	-0.01	1.00					
CN	0.56	-0.09	-0.34	0.06	-0.64	1.00				
$I2_a$	0.03	-0.68	-0.56	0.83	-0.16	0.23	1.00			
MAP	0.76	0.02	-0.43	0.06	-0.59	0.64	0.23	1.00		
MAE	-0.62	-0.02	0.40	-0.06	0.62	-0.65	-0.19	-0.87	1.00	
MAD	-0.72	-0.03	0.43	-0.07	0.63	-0.67	-0.22	-0.97	0.96	1.00

Table 3.2: Correlation matrix for C25 and possible explanatory variables

	C25	A	Sh	Sl	SP	CN	$I25_a$	MAP	MAE	MAD
C25	1.00									
A	-0.01	1.00								
Sh	-0.26	0.41	1.00							
Sl	-0.13	-0.50	-0.42	1.00						
SP	-0.35	-0.01	0.14	-0.01	1.00					
CN	0.37	-0.09	-0.34	0.06	-0.64	1.00				
$I25_a$	-0.01	-0.70	-0.57	0.83	-0.13	0.21	1.00			
MAP	0.58	0.02	-0.43	0.06	-0.59	0.64	0.20	1.00		
MAE	-0.46	-0.02	0.40	-0.06	0.62	-0.65	-0.16	-0.87	1.00	
MAD	-0.54	-0.03	0.43	-0.07	0.63	-0.67	-0.19	-0.97	0.96	1.00

Table 3.3: Correlation matrix for C100 and possible explanatory variables

	C100	A	Sh	Sl	SP	CN	$I100_a$	MAP	MAE	MAD
C100	1.00									
A	0.00	1.00								
Sh	-0.17	0.41	1.00							
Sl	-0.14	-0.50	-0.42	1.00						
SP	-0.28	-0.01	0.14	-0.01	1.00					
CN	0.27	-0.09	-0.34	0.06	-0.64	1.00				
$I100_a$	-0.05	-0.71	-0.57	0.83	-0.12	0.20	1.00			
MAP	0.45	0.02	-0.43	0.06	-0.59	0.64	0.20	1.00		
MAE	-0.38	-0.02	0.40	-0.06	0.62	-0.65	-0.16	-0.87	1.00	
MAD	-0.43	-0.03	0.43	-0.07	0.63	-0.67	-0.18	-0.97	0.96	1.00

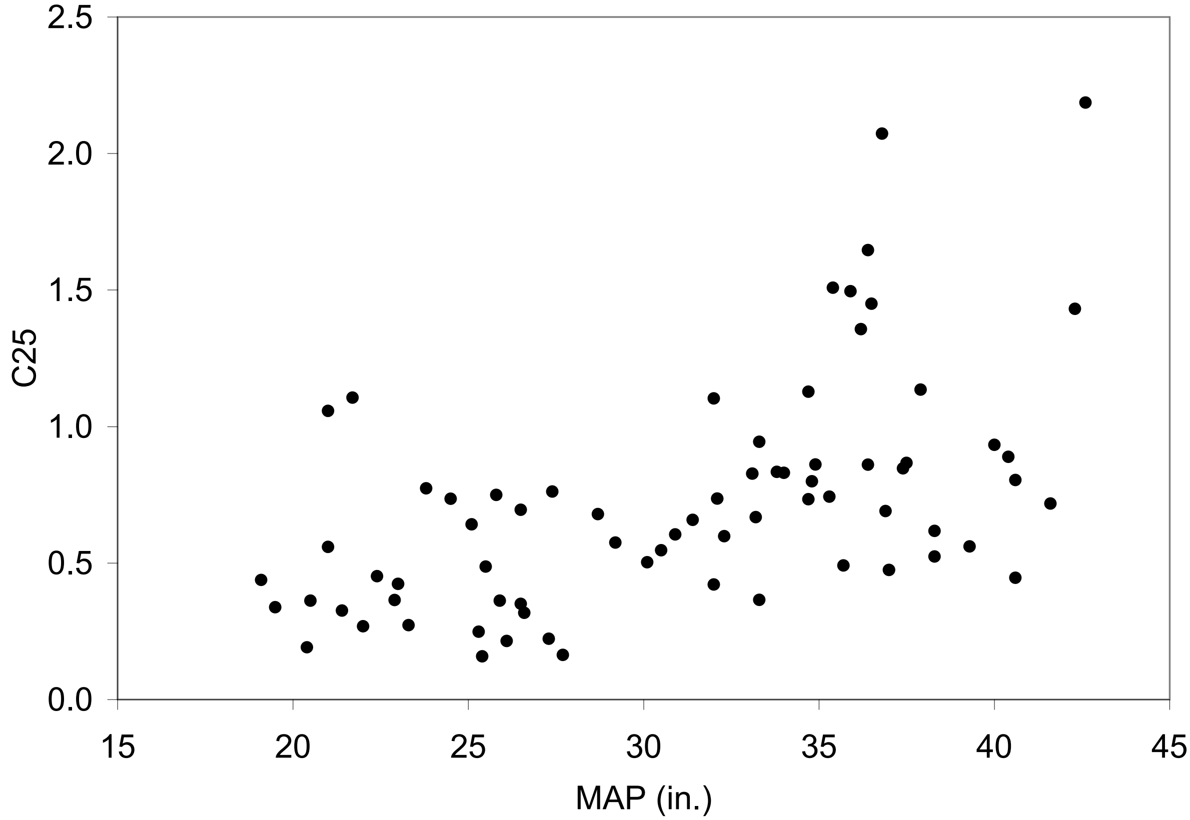

Figure 3.1: Scatter plot of C25 and MAP

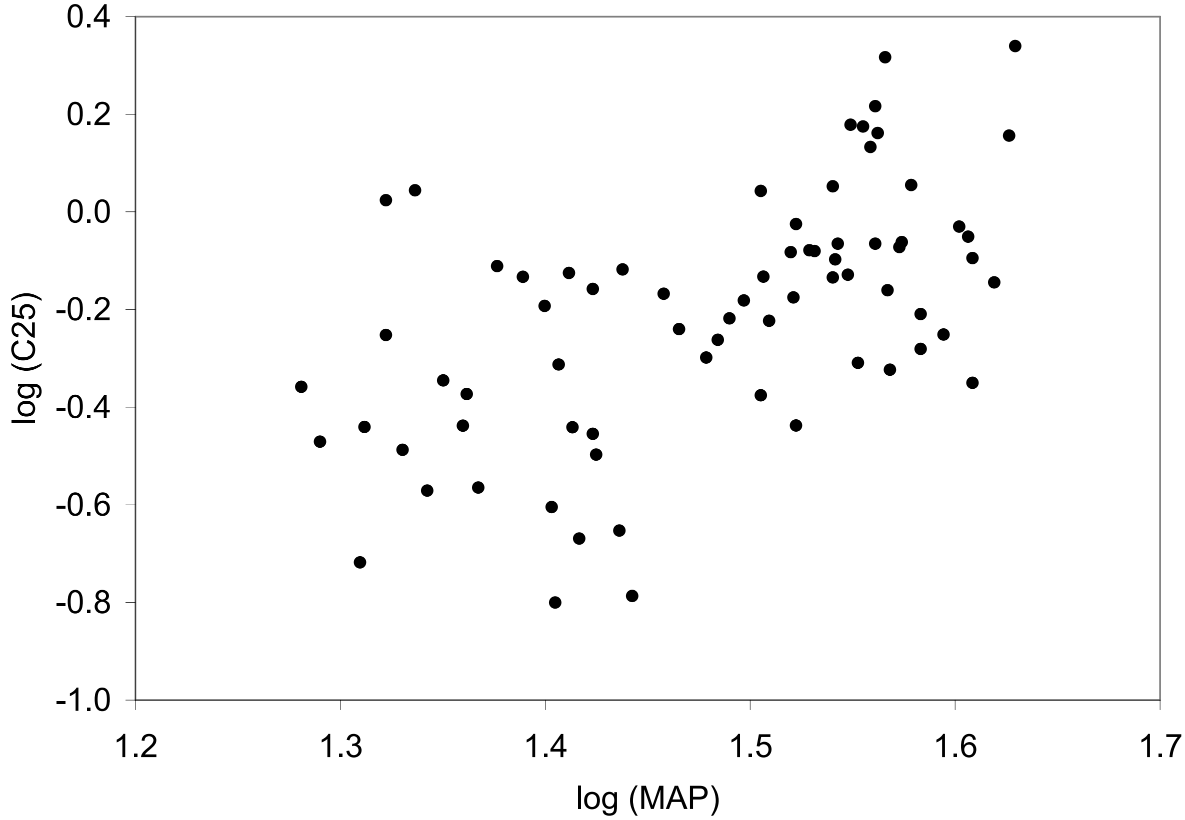

Figure 3.2: Scatter plot of logarithms of C25 and MAP

Table 3.4: Correlation matrix for logarithms of C2 and possible explanatory variables

	C2	A	Sh	Sl	SP	CN	$I2_a$	MAP	MAE	MAD
C2	1.00									
A	0.00	1.00								
Sh	-0.38	0.47	1.00							
Sl	-0.05	-0.76	-0.62	1.00						
SP	-0.54	0.10	0.18	-0.04	1.00					
CN	0.60	-0.14	-0.30	0.03	-0.70	1.00				
$I2_a$	0.19	-0.91	-0.74	0.88	-0.19	0.26	1.00			
MAP	0.79	-0.03	-0.41	0.07	-0.64	0.68	0.27	1.00		
MAE	-0.66	0.00	0.39	-0.08	0.65	-0.65	-0.23	-0.89	1.00	
MAD	-0.72	-0.03	0.44	-0.03	0.53	-0.56	-0.21	-0.93	0.89	1.00

Table 3.5: Correlation matrix for logarithms of C25 and possible explanatory variables

	C25	A	Sh	Sl	SP	CN	$I25_a$	MAP	MAE	MAD
C25	1.00									
A	0.07	1.00								
Sh	-0.23	0.47	1.00							
Sl	-0.02	-0.76	-0.62	1.00						
SP	-0.42	0.10	0.18	-0.04	1.00					
CN	0.37	-0.14	-0.30	0.03	-0.70	1.00				
$I25_a$	0.08	-0.92	-0.74	0.89	-0.16	0.23	1.00			
MAP	0.57	-0.03	-0.41	0.07	-0.64	0.68	0.24	1.00		
MAE	-0.47	0.00	0.39	-0.08	0.65	-0.65	-0.19	-0.89	1.00	
MAD	-0.55	-0.03	0.44	-0.03	0.53	-0.56	-0.18	-0.93	0.89	1.00

Table 3.6: Correlation matrix for logarithms of C100 and possible explanatory variables

	C100	A	Sh	Sl	SP	CN	$I100_a$	MAP	MAE	MAD
C100	1.00									
A	0.10	1.00								
Sh	-0.15	0.47	1.00							
Sl	-0.02	-0.76	-0.62	1.00						
SP	-0.34	0.10	0.18	-0.04	1.00					
CN	0.27	-0.14	-0.30	0.03	-0.70	1.00				
$I100_a$	0.03	-0.92	-0.74	0.89	-0.15	0.23	1.00			
MAP	0.44	-0.03	-0.41	0.07	-0.64	0.68	0.23	1.00		
MAE	-0.39	0.00	0.39	-0.08	0.65	-0.65	-0.18	-0.89	1.00	
MAD	-0.44	-0.03	0.44	-0.03	0.53	-0.56	-0.17	-0.93	0.89	1.00

The results of these correlation analyses led us to develop and evaluate alternative regression models for the runoff coefficients. We assessed the significance of the each predictor variable in each regression model with the following hypothesis test, in which b is the regression coefficient for the variable:

H_o: $b = 0$

H_1: $b \neq 0$

Reject H_o if $p < 0.05$ (95% confidence level)

The predictor variables in the multiple regression models were also checked for multicollinearity (redundancy) by computing the variance inflation factor (VIF) diagnostic for each variable. VIF > 10 indicates a potentially serious degree of multicollinearity. If any of the variables in a regression model was found to be insignificant or redundant, the model was discarded. The surviving regression models were compared on the basis of their standard errors of estimate.

First, we compared one-variable regression models with MAP and MAD as the predictor variable. We found that MAP and MAD work equally well at the 100-year recurrence interval, but MAP yields slightly better results at the shorter recurrence intervals. Next, we compared two-variable regression models with MAP as the first variable and SP, CN and Sh as the second variable. None of the two-variable regression models were satisfactory. In each case, the second coefficient failed the significance test. Therefore, we recommend the one-variable regression model with MAP as the explanatory variable for all recurrence intervals. Table 3.7 compares the results for five regression models for C25.

Table 3.7: Comparison of regression models for C25

Independent variables	Standard error of estimate (log units)	p-value for first variable	p-value for second variable
MAP	0.209	2.1×10^{-7}	-----
MAD	0.212	6.6×10^{-6}	-----
MAP, SP	0.210	1.8×10^{-4}	0.50
MAP, CN	0.211	5.3×10^{-5}	0.88
MAP, Sh	0.211	1.7×10^{-6}	0.95

The recommended regression equations for C2 through C100 and the corresponding Extended Rational equations for Q2 through Q100 are presented in Tables 3.8 and 3.9. These equations are applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas. The standard errors of estimate are lowest at the 5-year recurrence interval and highest at the 100-year recurrence interval. Figures 3.3 through 3.5 are scatter plots of the C2, C25 and C100 versus MAP for the 72 gaged watersheds, with the recommended regression equations superimposed. These graphs illustrate the considerable scatter in the data.

Table 3.8: Regression equations for Rational runoff coefficients

Recurrence interval (years)	Equation	Standard error of estimate	
		log units	%
2	$C2 = 0.0000366\ MAP^{2.53}$	0.192	+56%, -36%
5	$C5 = 0.000440\ MAP^{1.97}$	0.176	+50%, -33%
10	$C10 = 0.00137\ MAP^{1.72}$	0.187	+54%, -35%
25	$C25 = 0.00397\ MAP^{1.48}$	0.209	+62%, -38%
50	$C50 = 0.00724\ MAP^{1.35}$	0.227	+69%, -41%
100	$C100 = 0.0121\ MAP^{1.24}$	0.244	+76%, -43%

Note: Applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas.

Units: MAP in inches.

Table 3.9: Extended Rational equations

Recurrence interval (years)	Equation	Standard error of estimate	
		log units	%
2	$Q2 = 0.0236\ MAP^{2.53}\ I2_a\ A$	0.192	+56%, -36%
5	$Q5 = 0.284\ MAP^{1.97}\ I5_a\ A$	0.176	+50%, -33%
10	$Q10 = 0.884\ MAP^{1.72}\ I10_a\ A$	0.187	+54%, -35%
25	$Q25 = 2.56\ MAP^{1.48}\ I25_a\ A$	0.209	+62%, -38%
50	$Q50 = 4.67\ MAP^{1.35}\ I50_a\ A$	0.227	+69%, -41%
100	$Q100 = 7.81\ MAP^{1.24}\ I100_a\ A$	0.244	+76%, -43%

Note: Applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas.

Units: Q in cfs, MAP in inches, I_a in in./hr, A in mi^2

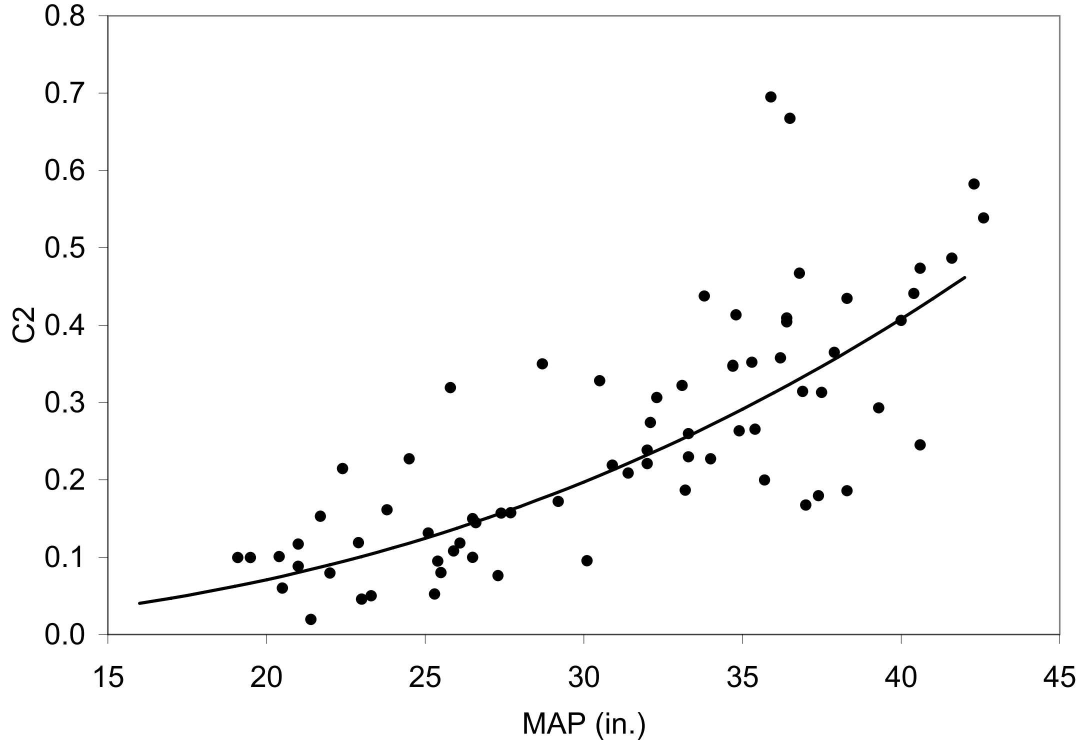

Figure 3.3: C2 vs. MAP for gaged watersheds, with fitted regression equation

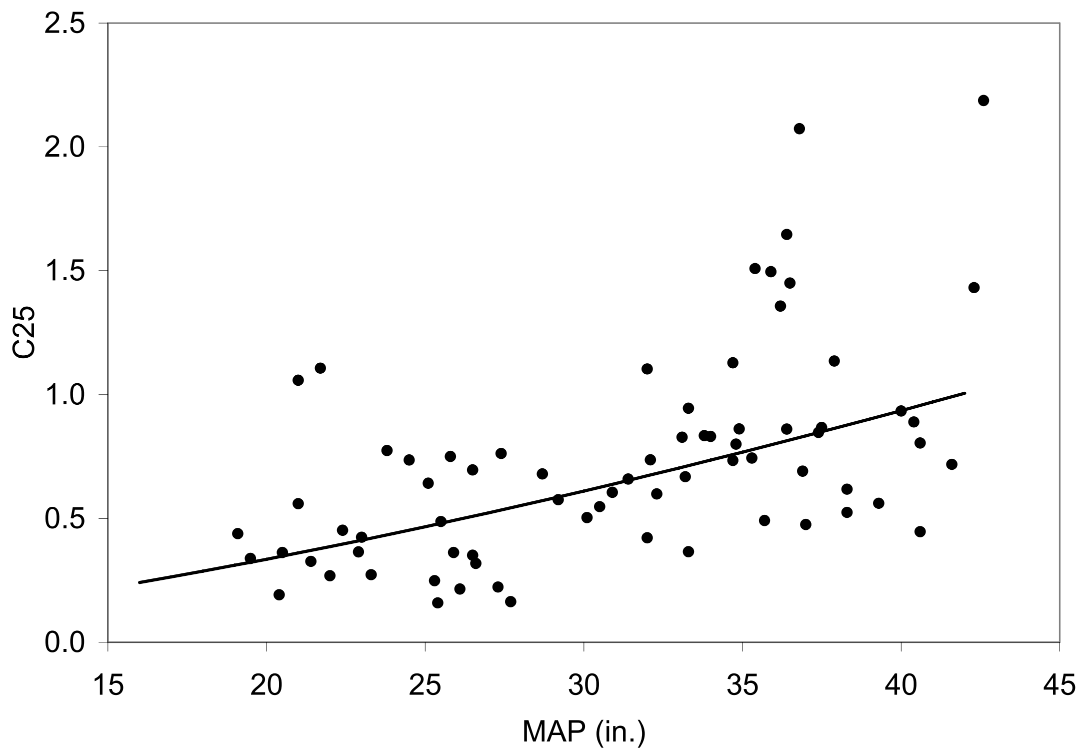

Figure 3.4: C25 vs. MAP for gaged watersheds, with fitted regression equation

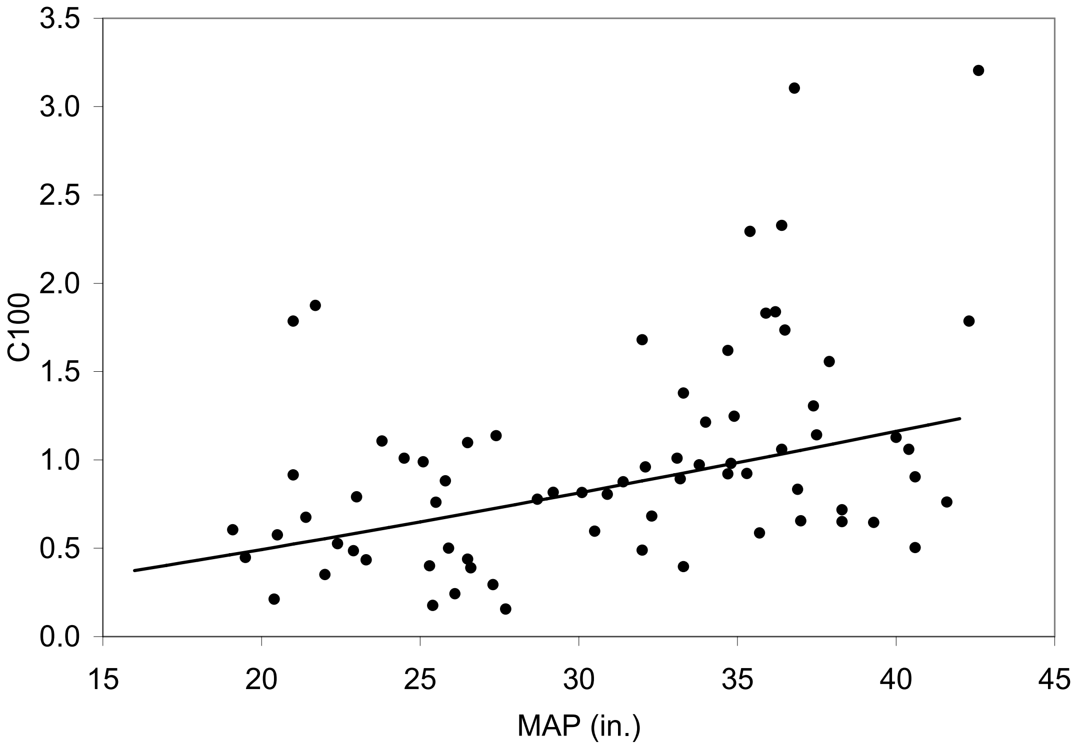

Figure 3.5: C100 vs. MAP for gaged watersheds, with fitted regression equation

Figure 3.6 displays the recommended relationships for C graphically. C varies greatly with both MAP and recurrence interval. As MAP increases, the variation in C with recurrence interval decreases in relative terms but increases in absolute terms. Likewise, as the recurrence interval increases, the variation in C with MAP decreases in relative terms but increases in absolute terms. Figures 3.7 through 3.12 show the how the runoff coefficients for the six recurrence intervals vary geographically across Kansas.

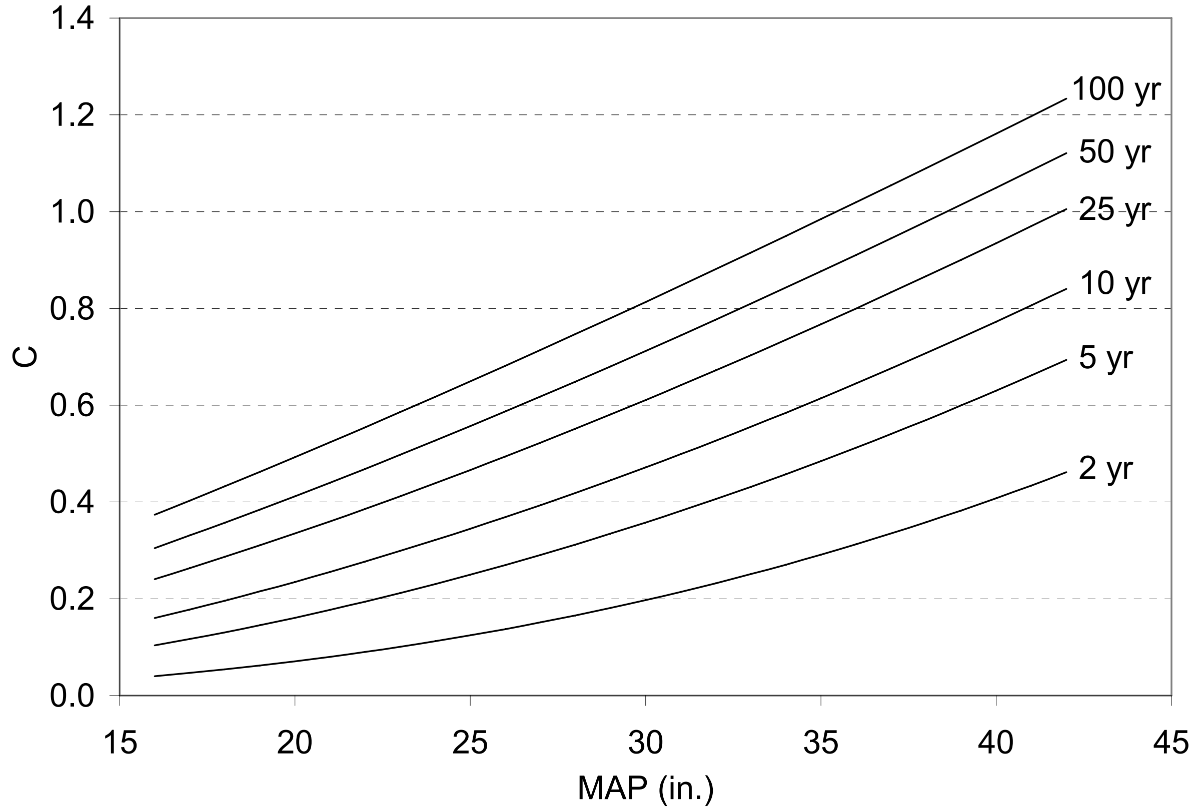

Figure 3.6: Variation of Rational C with mean annual precipitation and recurrence interval

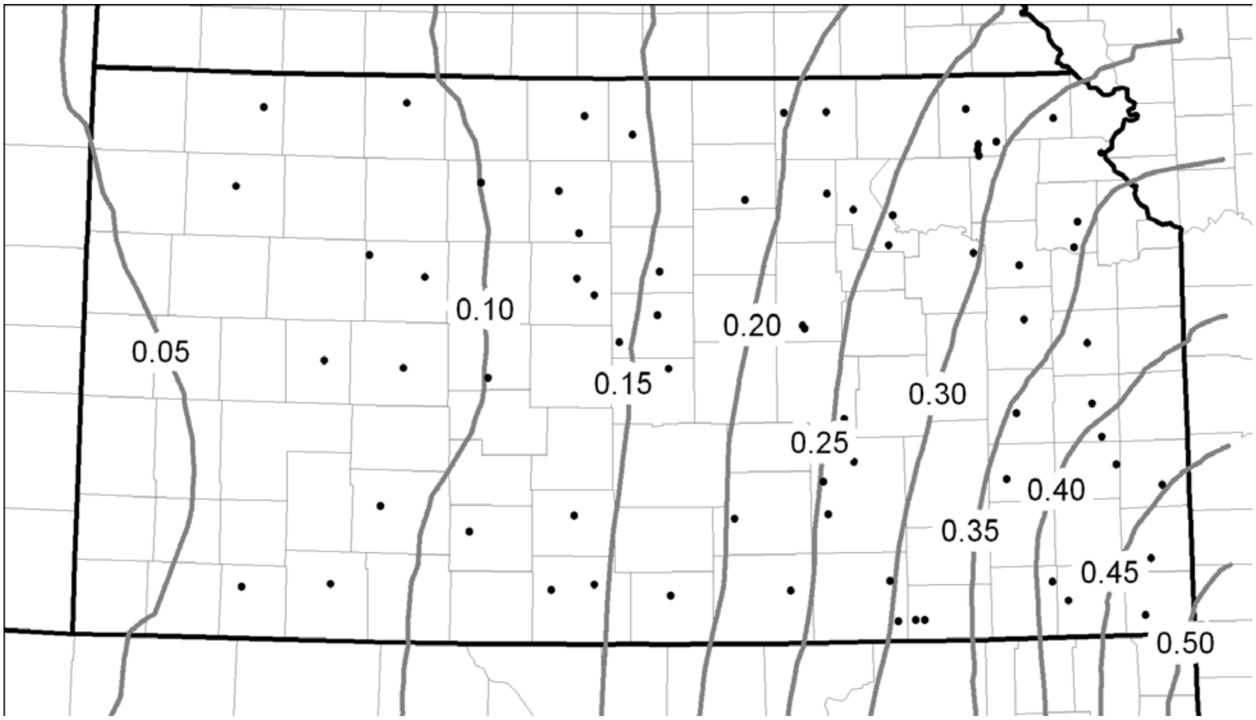

Figure 3.7: Rational C values for the 2-year recurrence interval (applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas)

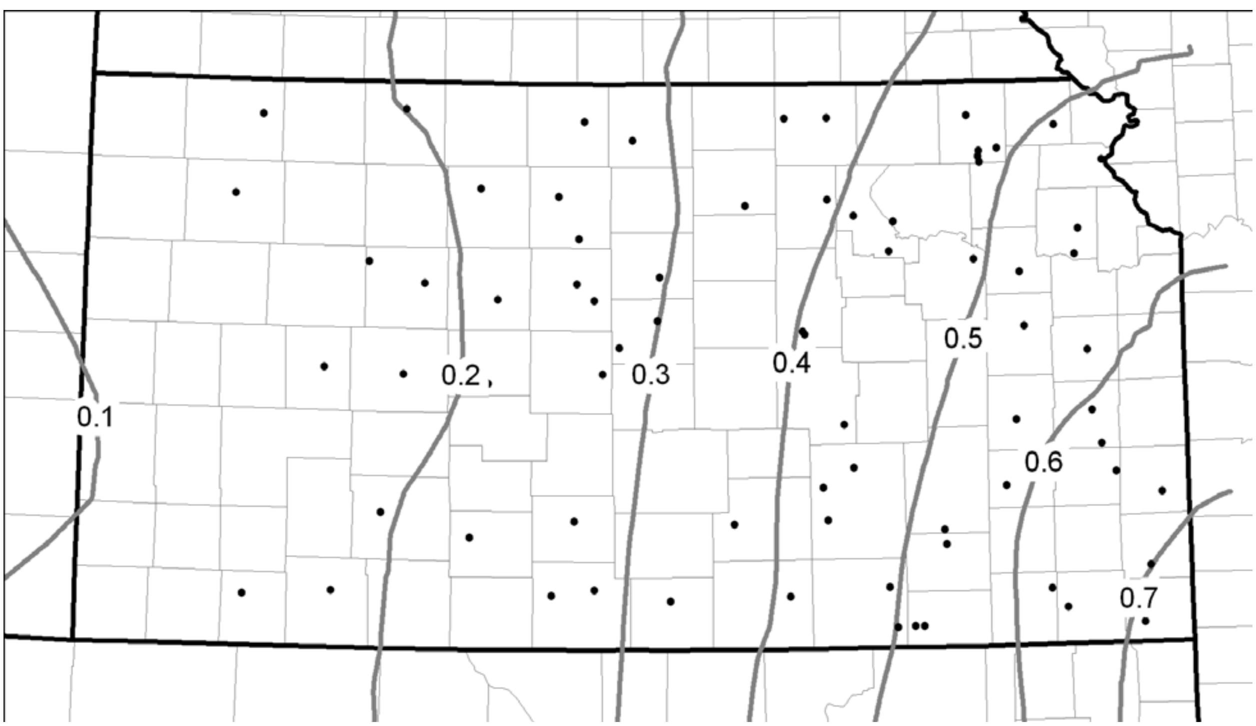

Figure 3.8: Rational C values for the 5-year recurrence interval (applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas)

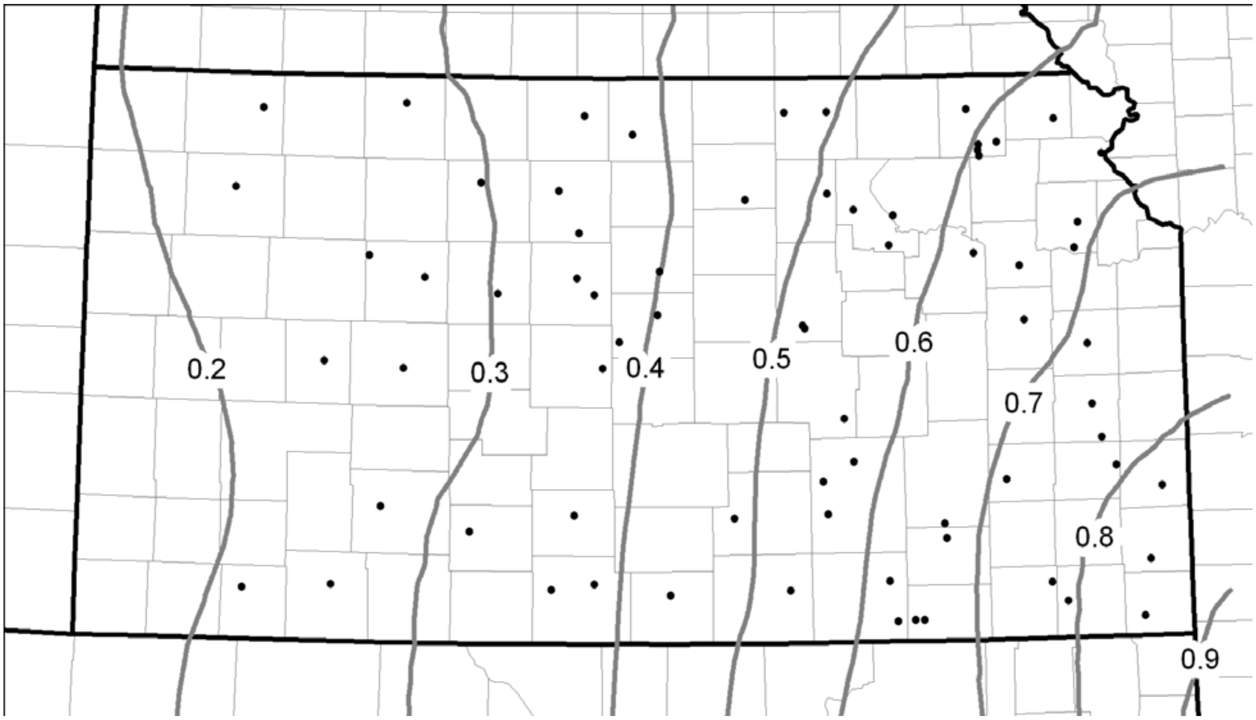

Figure 3.9: Rational C values for the 10-year recurrence interval (applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas)

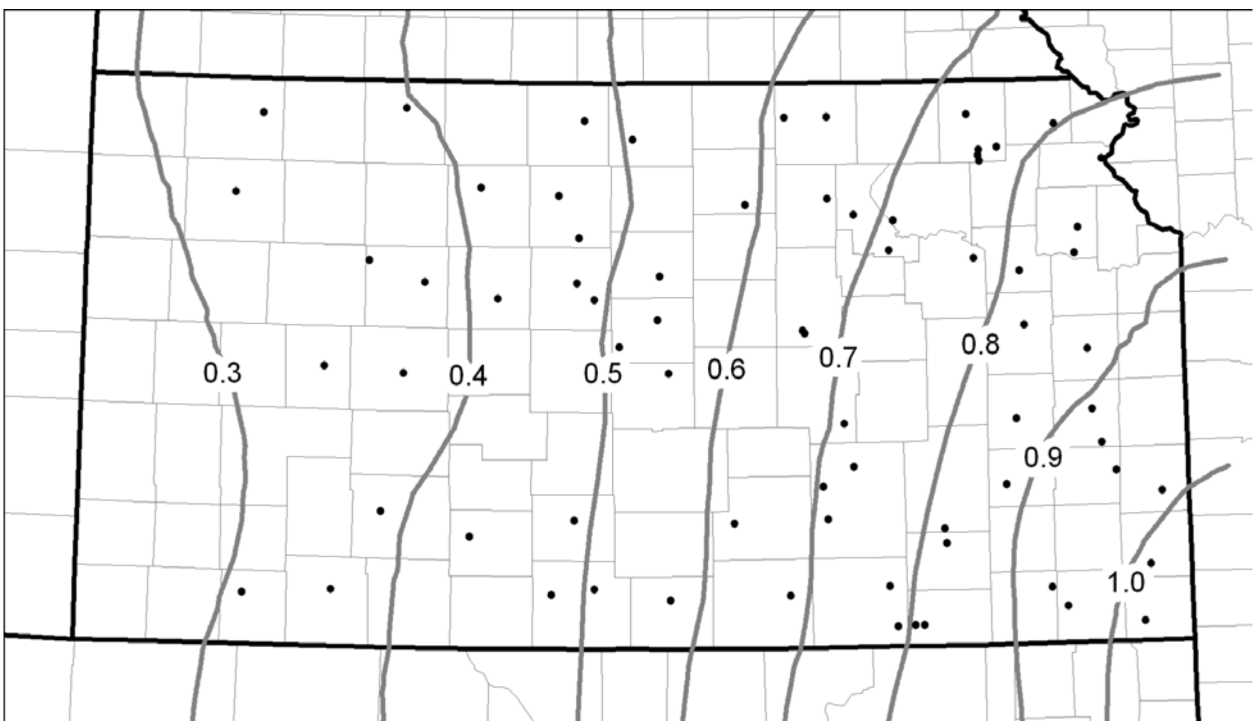

Figure 3.10: Rational C values for the 25-year recurrence interval (applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas)

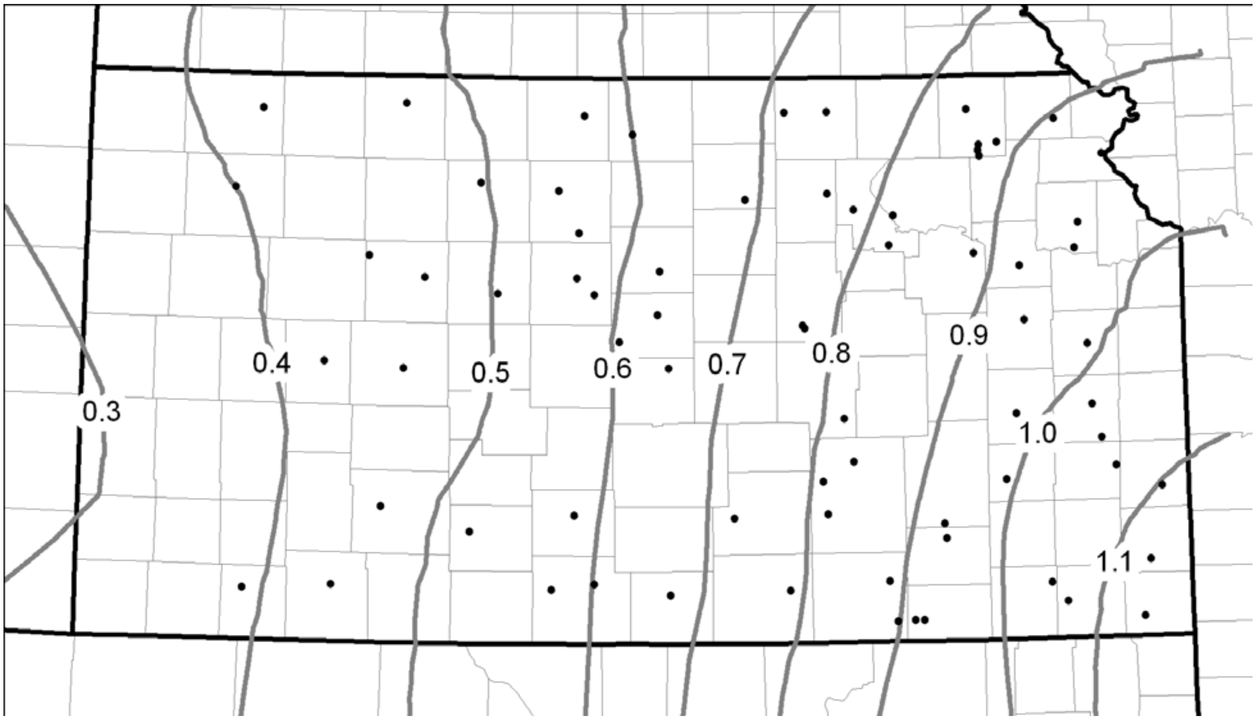

Figure 3.11: Rational C values for the 50-year recurrence interval (applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas)

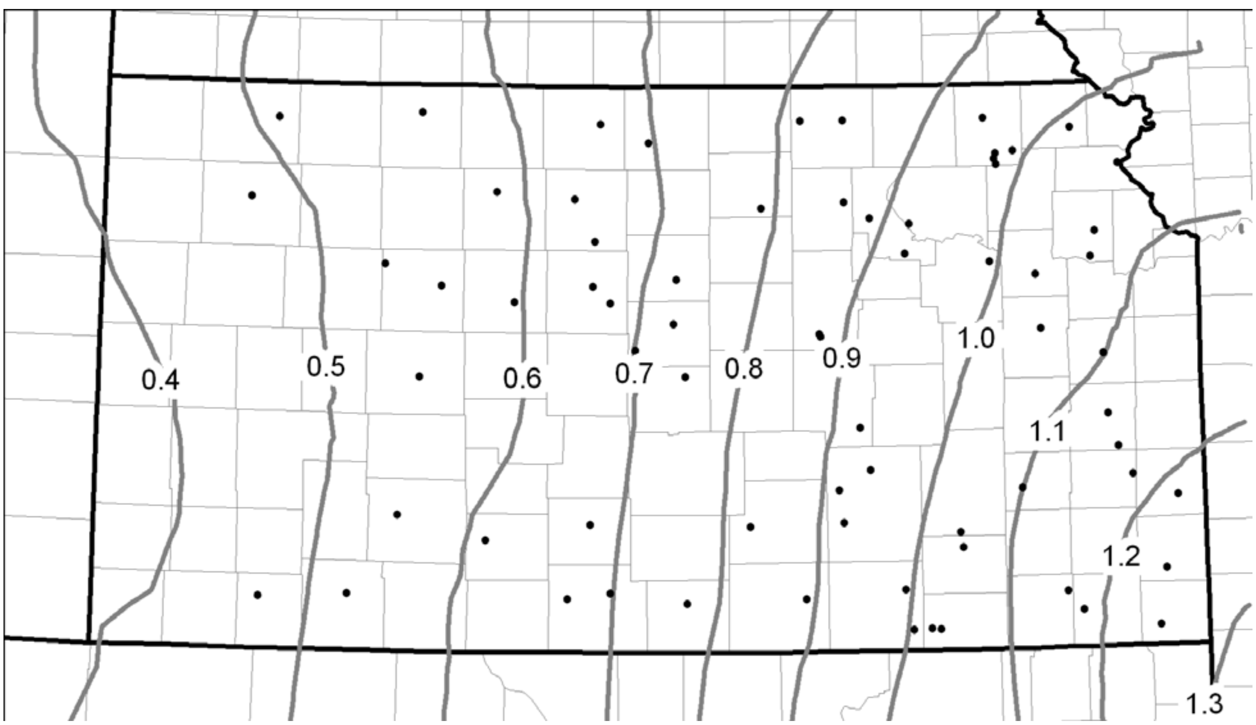

Figure 3.12: Rational C values for the 100-year recurrence interval (applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas)

3.2 Flood Discharges

The regression analyses for the flood discharges, like those for the runoff coefficients, were performed on the base-10 logarithms of the variables. Figure 3.13 shows the heteroscedasticity in the relationship between Q25 and drainage area, the most important predictor variable. Figure 3.14 shows that the relationship between log(Q25) and log(A) is more nearly homoscedastic.

Tables 3.10 through 3.12 show the correlation matrices for the logarithms of the flood discharges and possible explanatory variables for recurrence intervals of 2, 25 and 100 years. The correlation coefficients indicate that drainage area and the three climatic variables (MAP, MAE and MAD) have the greatest influence on the flood discharges. The C values are also moderately correlated with rainfall intensity, soil permeability and runoff curve number.

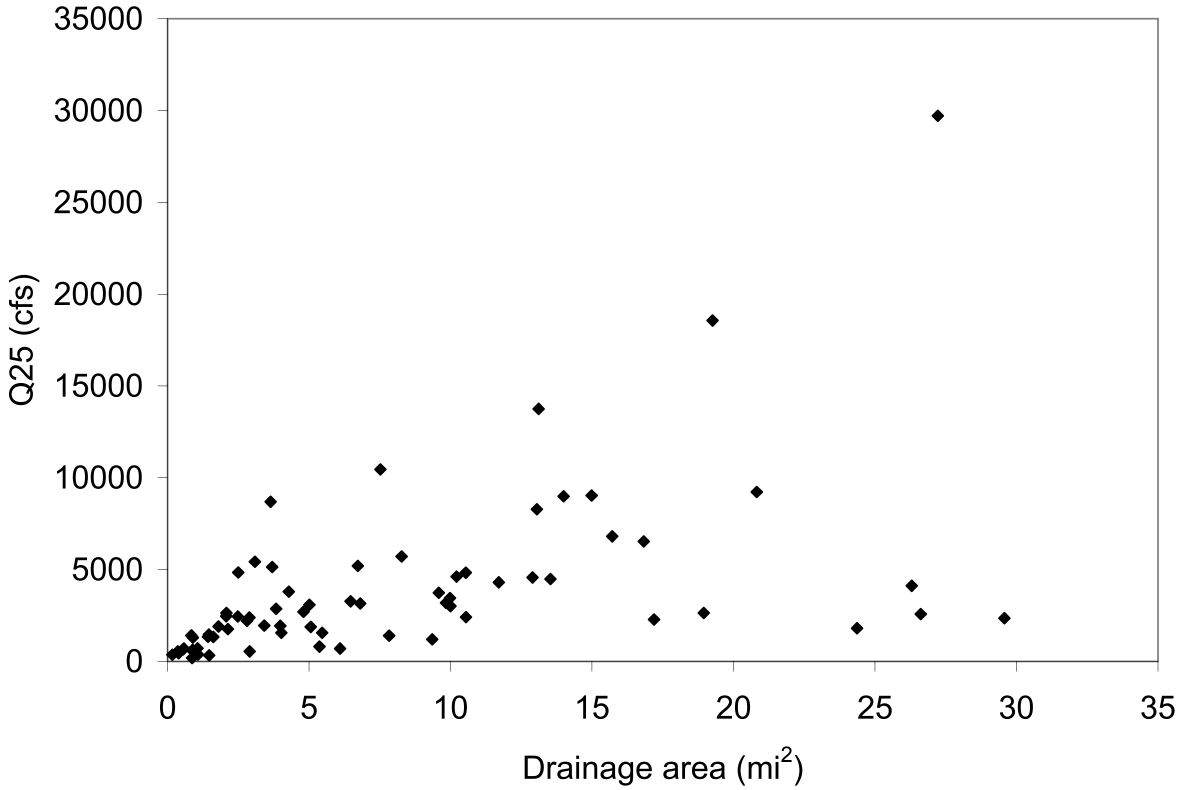

Figure 3.13: Scatter plot for Q25 and drainage area

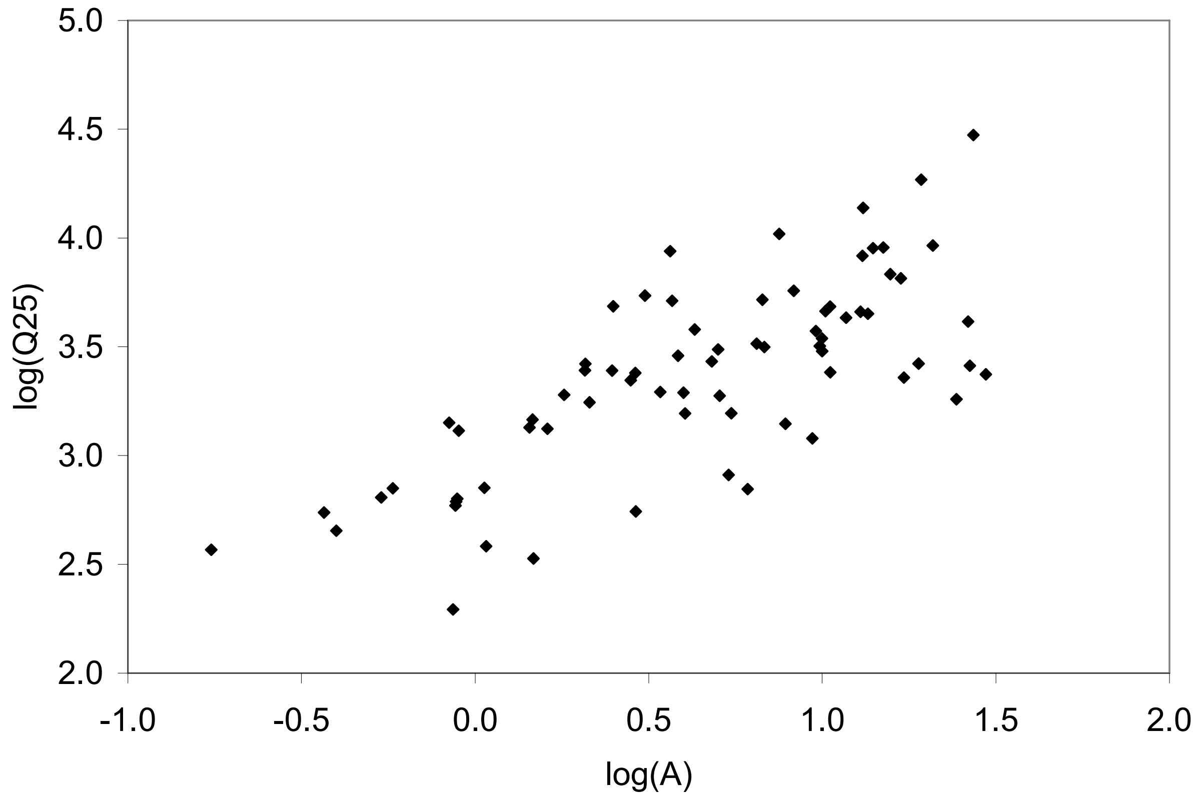

Figure 3.14: Scatter plot for logarithms of Q25 and drainage area

Table 3.10: Correlation matrix for logarithms of Q2 and possible explanatory variables

	Q2	A	Sh	Sl	SP	CN	$I2_a$	MAP	MAE	MAD
Q2	1.00									
A	0.63	1.00								
Sh	-0.12	0.47	1.00							
Sl	-0.41	-0.76	-0.62	1.00						
SP	-0.34	0.10	0.18	-0.04	1.00					
CN	0.38	-0.14	-0.30	0.03	-0.70	1.00				
$I2_a$	-0.36	-0.91	-0.74	0.88	-0.19	0.26	1.00			
MAP	0.62	-0.03	-0.41	0.07	-0.64	0.68	0.27	1.00		
MAE	-0.55	0.00	0.39	-0.08	0.65	-0.65	-0.23	-0.89	1.00	
MAD	-0.61	-0.03	0.44	-0.03	0.53	-0.56	-0.21	-0.93	0.89	1.00

Table 3.11: Correlation matrix for logarithms of Q25 and possible explanatory variables

	Q25	A	Sh	Sl	SP	CN	$I25_a$	MAP	MAE	MAD
Q25	1.00									
A	0.73	1.00								
Sh	0.03	0.47	1.00							
Sl	-0.44	-0.76	-0.62	1.00						
SP	-0.21	0.10	0.18	-0.04	1.00					
CN	0.18	-0.14	-0.30	0.03	-0.70	1.00				
$I25_a$	-0.51	-0.92	-0.74	0.89	-0.16	0.23	1.00			
MAP	0.41	-0.03	-0.41	0.07	-0.64	0.68	0.24	1.00		
MAE	-0.37	0.00	0.39	-0.08	0.65	-0.65	-0.19	-0.89	1.00	
MAD	-0.44	-0.03	0.44	-0.03	0.53	-0.56	-0.18	-0.93	0.89	1.00

Table 3.12: Correlation matrix for logarithms of Q100 and possible explanatory variables

	Q100	A	Sh	Sl	SP	CN	$I100_a$	MAP	MAE	MAD
Q100	1.00									
A	0.73	1.00								
Sh	0.07	0.47	1.00							
Sl	-0.43	-0.76	-0.62	1.00						
SP	-0.17	0.10	0.18	-0.04	1.00					
CN	0.12	-0.14	-0.30	0.03	-0.70	1.00				
$I100_a$	-0.52	-0.92	-0.74	0.89	-0.15	0.23	1.00			
MAP	0.34	-0.03	-0.41	0.07	-0.64	0.68	0.23	1.00		
MAE	-0.32	0.00	0.39	-0.08	0.65	-0.65	-0.18	-0.89	1.00	
MAD	-0.38	-0.03	0.44	-0.03	0.53	-0.56	-0.17	-0.93	0.89	1.00

These correlation results guided the development of alternative regression models for Q2 through Q100. Drainage area was included in all regression models. Table 3.13 compares the results for five regression models for Q25. The best two-variable regression model includes MAP as the second variable. Adding rainfall intensity as a third variable improves the relationship significantly. The rainfall intensity term is statistically significant ($p < 0.05$) and its VIF diagnostic for multicollinearity is within the acceptable range. The three-variable model with slope as the third variable is statistically valid but it has a larger standard error than the three-variable model that includes I_a. Channel slope is statistically insignificant ($p > 0.05$) in the four-variable model.

Table 3.13: Comparison of regression models for Q25

Independent Variables	Standard error of estimate (log units)	p-value for first variable	p-value for second variable	p-value for third variable	p-value for fourth variable
A, MAP	0.232	1.6×10^{-18}	1.3×10^{-9}	-----	-----
A, MAD	0.237	2.5×10^{-17}	7.1×10^{-9}	-----	-----
A, MAP, I_a	0.210	4.8×10^{-12}	2.6×10^{-5}	1.5×10^{-4}	-----
A, MAP, SI	0.223	4.5×10^{-15}	1.0×10^{-9}	1.2×10^{-2}	-----
A, MAP, I_a, SI	0.210	1.3×10^{-10}	0.0018	00027	0.32

Units: Q in cfs, MAP in inches, I_a in in./hr, A in mi^2

The recommended regression equations for Q2 through Q100 are the three-variable equations in Table 3.14. The best two-variable regression equations for Q2 through Q100 are shown in Table 3.15 for comparison.

Table 3.14: Three-variable regression equations for flood discharge

Recurrence interval (years)	Equation	Standard error of estimate	
		log units	%
2	$Q2 = 0.0229\ MAP^{2.53}\ I2_a^{1.00}\ A^{1.02}$	0.195	+57%, -36%
5	$Q5 = 0.323\ MAP^{1.90}\ I5_a^{1.14}\ A^{1.09}$	0.178	+51%, -34%
10	$Q10 = 1.01\ MAP^{1.62}\ I10_a^{1.19}\ A^{1.11}$	0.189	+54%, -35%
25	$Q25 = 2.86\ MAP^{1.36}\ I25_a^{1.24}\ A^{1.15}$	0.210	+62%, -38%
50	$Q50 = 5.01\ MAP^{1.23}\ I50_a^{1.27}\ A^{1.16}$	0.227	+69%, -41%
100	$Q100 = 8.07\ MAP^{1.11}\ I100_a^{1.29}\ A^{1.18}$	0.245	+76%, -43%

Note: Applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas.

Units: Q in cfs, MAP in inches, I_a in in./hr, A in mi^2

Table 3.15: Two-variable regression equations for flood discharge

Recurrence interval (years)	Equation	Standard error of estimate	
		log units	%
2	$Q2 = 0.00371\ A^{0.59}\ MAP^{3.16}$	0.210	+62%,-38%
5	$Q5 = 0.0722\ A^{0.61}\ MAP^{2.53}$	0.199	+58%, -37%
10	$Q10 = 0.278\ A^{0.62}\ MAP^{2.25}$	0.211	+62%, -38%
25	$Q25 = 1.01\ A^{0.63}\ MAP^{2.00}$	0.232	+70%, -41%
50	$Q50 = 2.16\ A^{0.64}\ MAP^{1.85}$	0.248	+77%, -44%
100	$Q100 = 4.04\ A^{0.65}\ MAP^{1.73}$	0.265	+84%, -46%

Note: Applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas.

Units: Q in cfs, A in mi^2, MAP in inches

3.3 Evaluation and Comparison of the New Equations

Table 3.16 compares the standard errors of estimate for the Extended Rational equations and the three-variable and two-variable regression equations for Q2 through Q100. The Extended Rational equations and the three-variable regression equations for discharge have nearly identical standard errors. The two-variable regression equations, which are similar to the current USGS regression equations for Kansas watersheds under 30 mi^2, have larger standard errors.

Rainfall intensity of the appropriate duration and recurrence interval is clearly a significant predictor of flood discharge. Inclusion of this variable in the regression analysis for flood discharge led to three-variable regression equations that closely resemble the Extended Rational equations. The two sets of equations include the same three variables, and the exponents on the variables differ only slightly.

The Extended Rational equations in Table 3.9 and the three-variable regression equations in Table 3.14 provide equally valid estimates of flood discharges for rural watersheds under 30 mi^2 in Kansas.

Table 3.16: Comparison of standard errors for three sets of equations for flood discharge

Recurrence interval (years)	Standard error of estimate (%)		
	Extended Rational equations	Three-variable regression equations	Two-variable regression equations
2	+56%, -36%	+57%, -36%	+62%, -38%
5	+50%, -33%	+51%, -34%	+58%, -37%
10	+54%, -35%	+54%, -35%	+62%, -38%
25	+62%, -38%	+62%, -38%	+70%, -41%
50	+69%, -41%	+69%, -41%	+77%, -44%
100	+76%, -43%	+76%, -43%	+84%, -46%

CHAPTER 4 - APPLICATION OF THE NEW EQUATIONS

4.1 Step-by-Step Procedure

The Extended Rational equations in Table 3.9 and the three-variable regression equations in Table 3.14 provide estimates of the 2-year through 100-year discharges for unregulated rural streams with drainage areas under 30 mi^2 in Kansas. To estimate the T-year discharge with one of these equations, follow the steps below.

1. Delineate the watershed boundary on a USGS topographic map.
2. Measure the drainage area, A, in mi^2.
3. Identify the main channel on the topographic map and extend it upstream to the watershed divide (perpendicular to the elevation contours).
4. Measure the length of the main channel, L, in miles, following the twists and turns.
5. Identify points along the channel at 10% and 85% of L upstream of the watershed outlet.
6. Determine the elevations at these two points.
7. Compute the average channel slope, Sl, in ft/ft. The average channel slope is defined as the elevation difference between the 85% and 10% points on the main channel, divided by the intervening distance (0.75 L).

7\. Compute the time of concentration, t_c, in hours with Eq 2.2.

8\. Locate KDOT's rainfall intensity table for the county that contains the centroid of the watershed. Look up the rainfall intensity for the desired recurrence interval and a duration equal to the time of concentration. Interpolate linearly for duration as needed.

9. Locate the centroid of the watershed on the map of mean annual precipitation in Figure 2.4. Find the mean annual precipitation in inches at the centroid by interpolation.

10. Calculate the discharge with the equation for the desired recurrence interval from Table 3.9 or Table 3.14.

4.2 Example Application

Problem

A stream crossing in southwestern Nemaha County has a drainage area of 9.87 mi^2. The length of the main channel is 6.54 mi and the average slope of the main channel is 0.0032 ft/ft. Compute estimates of the 50-year discharge (Q50) using (1) the Extended Rational equation for Q50 and (2) the three-variable regression equation for Q50.

Solution

1. Compute the time of concentration with Eq. 2.2.

$$t_c = 0.176\left(\frac{L}{\sqrt{S}}\right)^{0.66} = 0.176\left(\frac{6.54}{\sqrt{0.0032}}\right)^{0.66} = 4.05\ \text{hr}$$

2. Obtain the 50-year point-rainfall intensity for a duration of 4.05 hours by interpolation in KDOT's rainfall intensity table for Nemaha County.

   $I50_p$ = 1.11 in./hr

3. Compute the corresponding 50-year rainfall intensity over the 9.87-mi^2 watershed with Eq. 2.5.

$$\begin{aligned} I50_a &= I50_p \left[1-\left(0.355\, t_c^{-0.428}\right)\left(1-e^{-0.015\,A}\right)\right] \\ &= 1.11\left\{1-\left[0.355\left(4.05\right)^{-0.428}\right]\left[1-e^{-0.015(9.87)}\right]\right\} \\ &= 1.08 \text{ in./hr} \end{aligned}$$

4. Obtain the mean annual precipitation for southwestern Nemaha County from Figure 2.4.

MAP = 34.0 in.

5. Compute Q50 with the Extended Rational equation from Table 3.9.

$$\begin{aligned} Q50 &= 4.67\ (MAP)^{1.35}\ I50_a\ A \\ &= 4.67\ (34.0)^{1.35}\ (1.08)\ (9.87) \\ &= 5820 \text{ cfs} \end{aligned}$$

6. Compute Q50 with the three-variable regression equation from Table 3.14.

$$\begin{aligned} Q50 &= 5.01\ MAP^{1.23}\ I50_a^{1.27}\ A^{1.16} \\ &= 5.01\ (34.0)^{1.23}\ (1.08)^{1.27}\ (9.87)^{1.16} \\ &= 6020 \text{ cfs} \end{aligned}$$

The two estimates are equally valid. Both estimates have standard errors of +69%, -41%.

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APPENDIX

Table A.1: USGS streamflow-gaging records in data set

USGS station number	Station name	County	Drainage area (mi^2)	Years of record
6813700	Tennessee Creek tributary near Seneca	Nemaha	0.897	33
6815700	Buttermilk Creek near Willis	Brown	3.696	46
6818260	White Clay Creek at Atchison	Atchison	12.897	32
6846200	Beaver Creek tributary near Ludell	Rawlins	10.548	33
6847600	Prairie Dog Creek tributary at Colby	Thomas	7.831	47
6848200	Prairie Dog Creek tributary near Norton	Norton	1.064	35
6856800	Moll Creek near Green	Clay	3.983	34
6863400	Big Creek tributary near Ogallah	Trego	4.809	48
6863700	Big Creek tributary near Hays	Ellis	6.095	46
6864300	Smoky Hill River tributary at Dorrance	Russell	5.466	48
6864700	Spring Creek near Kanopolis	Ellsworth	9.589	33
6866800	Saline River tributary at Collyer	Trego	3.417	33
6867800	Cedar Creek tributary near Bunker Hill	Russell	1.075	21
6868300	Coon Creek tributary near Luray	Osborne	6.470	48
6868900	Bullfoot Creek tributary near Lincoln	Lincoln	2.902	33
6872600	Oak Creek at Bellaire	Smith	5.373	33
6873300	Ash Creek tributary near Stockton	Rooks	0.877	47
6873800	Kill Creek tributary near Bloomington	Osborne	1.435	21
6874500	East Limestone Creek near Ionia	Jewell	26.618	38
6876200	Middle Pipe Creek near Miltonvale	Cloud	9.841	21
6877200	West Turkey Creek near Elmo	Dickinson	26.301	21
6877400	Turkey Creek tributary near Elmo	Dickinson	2.482	21
6879700	Wildcat Creek at Riley	Riley	13.538	21
6884100	Mulberry Creek tributary near Haddam	Washington	1.616	32
6884300	Mill Creek tributary near Washington	Washington	2.895	47
6887200	Cedar Creek near Manhattan	Pottawatomie	14.002	48
6888600	Dry Creek near Maple Hill	Wabaunsee	15.715	22
6889100	Soldier Creek near Goff	Nemaha	2.071	23
6889120	Soldier Creek near Bancroft	Nemaha	10.538	24
6889140	Soldier Creek near Soldier	Nemaha	16.831	34
6889600	S. Branch Shunganunga Creek near Pauline	Shawnee	3.841	21
6890300	Spring Creek near Wetmore	Nemaha	20.823	21
6890700	Slough Creek tributary near Oskaloosa	Jefferson	0.842	21
6891050	Stone House Creek at Williamstown	Jefferson	13.053	26
6912300	Dragoon Creek tributary near Lyndon	Osage	3.644	34
6913600	Rock Creek near Ottawa	Franklin	10.001	21

Table A.1: USGS streamflow-gaging records in data set (continued)

USGS station number	Station name	County	Drainage area (mi^2)	Years of record
6914250	S. Fork Pottawatomie Cr. trib. near Garnett	Anderson	0.367	40
6916700	Middle Creek near Kincaid	Anderson	2.078	34
6917100	Marmaton River tributary near Bronson	Allen	0.888	34
6917400	Marmaton River tributary near Fort Scott	Bourbon	2.809	48
7139700	Arkansas River tributary near Dodge City	Ford	9.359	46
7141400	South Fork Walnut Creek trib. near Dighton	Lane	0.864	21
7141600	Long Branch Creek near Ness City	Ness	29.575	33
7141800	Otter Creek near Rush Center	Rush	17.197	33
7142100	Rattlesnake Creek tributary near Mullinville	Kiowa	9.984	33
7143100	Little Cheyenne Creek tributary near Clafin	Barton	1.472	48
7143200	Plum Creek near Holyrood	Ellsworth	18.948	21
7143500	Little Arkansas River near Geneseo	Rice	24.367	21
7144900	South Fork Ninnescah River trib. near Pratt	Pratt	1.464	33
7145300	Clear Creek near Garden Plain	Sedgewick	5.061	33
7145800	Antelope Creek tributary near Dalton	Sumner	0.398	34
7146700	W. Branch Walnut River trib. near Degraff	Butler	10.214	21
7147020	Whitewater River tributary near Towanda	Butler	0.174	41
7147200	Dry Creek tributary near Augusta	Butler	0.882	21
7147990	Cedar Creek tributary near Cambridge	Cowley	2.500	44
7148700	Dog Creek near Deerhead	Barber	5.016	21
7148800	Medicine Lodge R. trib. nr. Medicine Lodge	Barber	2.135	21
7151600	Rush Creek near Harper	Harper	11.711	33
7156700	Cimarron River tributary near Satanta	Seward	4.026	47
7157400	Crooked Creek tributary at Meade	Meade	6.724	33
7166200	Sandy Creek near Yates Center	Woodson	6.812	48
7169200	Salt Creek near Severy	Greenwood	7.522	21
7169700	Snake Creek near Howard	Elk	1.804	21
7170600	Cherry Creek near Cherryvale	Montgomery	14.987	21
7170800	Mud Creek near Mound Valley	Labette	4.288	34
7171700	Spring Branch near Cedar Vale	Chautauqua	3.086	38

Table A.1: USGS streamflow-gaging records in data set (continued)

USGS station number	Station name	County	Drainage area (mi^2)	Years of record
7171800	Cedar Creek tributary near Hooser	Cowley	0.536	34
7171900	Grant Creek near Wauneta	Chautauqua	19.263	21
7180300	Spring Creek tributary near Florence	Marion	0.579	34
7182520	Rock Creek at Burlington	Coffey	8.270	21
7183800	Limestone Creek near Beulah	Crawford	13.117	33
7184600	Fly Creek near Faulkner	Cherokee	27.224	21

Table A.2: Flood discharges from frequency analysis of station data

USGS station number	Q2 (cfs)	Q5 (cfs)	Q10 (cfs)	Q100 (cfs)	Q50 (cfs)	Q100 (cfs)
6813700	201	497	794	1300	1785	2370
6815700	1360	2604	3631	5146	6428	7836
6818260	920	1979	2965	4575	6066	7825
6846200	203	714	1311	2414	3510	4852
6847600	216	560	886	1401	1854	2360
6848200	184	366	509	710	871	1039
6856800	348	821	1257	1947	2560	3256
6863400	196	735	1403	2705	4062	5787
6863700	72	222	390	701	1012	1401
6864300	247	617	976	1565	2104	2731
6864700	414	1255	2157	3740	5258	7073
6866800	162	566	1046	1957	2885	4049
6867800	131	223	291	383	455	530
6868300	353	1073	1860	3269	4650	6333
6868900	104	239	361	554	724	916
6872600	94	267	459	815	1177	1636
6873300	35	143	287	590	927	1381
6873800	228	549	852	1346	1795	2314
6874500	645	1274	1801	2586	3253	3987
6876200	535	1274	1991	3187	4308	5639
6877200	1194	2214	3009	4126	5028	5981
6877400	292	840	1424	2456	3459	4676
6879700	932	2017	2983	4487	5813	7314
6884100	142	424	741	1328	1925	2678
6884300	488	1056	1573	2395	3135	3988
6887200	1361	3395	5449	8991	12400	16530
6888600	1784	3399	4760	6813	8587	10570
6889100	428	988	1535	2462	3346	4413
6889120	1280	2407	3367	4837	6126	7588
6889140	1888	3404	4658	6534	8149	9954
6889600	767	1455	2026	2874	3597	4397

Table A.2: Flood discharges from frequency analysis of station data (continued)

USGS station number	Q2 (cfs)	Q5 (cfs)	Q10 (cfs)	Q100 (cfs)	Q50 (cfs)	Q100 (cfs)
6890300	1612	3687	5731	9232	12610	16720
6890700	172	485	821	1417	2002	2719
6891050	1708	3709	5498	8293	10760	13570
6912300	1136	3107	5150	8694	12090	16180
6913600	601	1303	1955	3017	3993	5141
6914250	169	303	405	547	661	779
6916700	673	1334	1870	2641	3275	3952
6917100	199	356	474	634	759	889
6917400	872	1393	1754	2220	2571	2922
7139700	185	486	766	1199	1572	1981
7141400	56	107	146	196	234	273
7141600	74	432	1009	2362	3974	6228
7141800	394	955	1472	2284	2997	3796
7142100	380	1191	2037	3455	4749	6226
7143100	98	182	247	336	407	481
7143200	608	1251	1804	2645	3373	4185
7143500	956	1319	1544	1813	2003	2185
7144900	344	727	1034	1463	1804	2157
7145300	598	1073	1421	1884	2238	2597
7145800	134	247	334	452	544	640
7146700	1314	2445	3341	4616	5660	6777
7147020	85	180	257	369	460	556
7147200	226	373	477	614	719	825
7147990	480	1568	2761	4850	6833	9175
7148700	272	938	1699	3079	4426	6053
7148800	135	507	948	1757	2548	3499
7151600	1193	2286	3134	4306	5236	6203
7156700	189	567	946	1562	2110	2723
7157400	293	1300	2617	5205	7867	11180
7166200	1204	1948	2473	3158	3679	4206
7169200	2628	5259	7392	10450	12960	15630
7169700	499	970	1351	1901	2355	2842
7170600	2460	4653	6437	9041	11220	13600
7170800	1279	2180	2858	3794	4541	5327
7171700	808	2148	3421	5433	7194	9154
7171800	157	323	456	641	789	943
7171900	2471	6865	11260	18560	25230	32920
7180300	115	291	454	708	929	1173
7182520	1024	2375	3648	5720	7617	9827
7183800	3127	6534	9428	13750	17410	21430
7184600	4193	11020	17930	29710	40860	54150

Table A.3: Rational runoff coefficients from station data

USGS station number	C2	C5	C10	C25	C50	C100
6813700	0.23	0.44	0.60	0.83	1.02	1.21
6815700	0.69	1.04	1.25	1.50	1.67	1.83
6818260	0.17	0.28	0.37	0.47	0.56	0.65
6846200	0.06	0.15	0.24	0.36	0.47	0.58
6847600	0.10	0.19	0.26	0.34	0.39	0.45
6848200	0.21	0.32	0.39	0.45	0.49	0.53
6856800	0.21	0.38	0.51	0.66	0.77	0.88
6863400	0.15	0.42	0.70	1.11	1.48	1.87
6863700	0.05	0.12	0.18	0.27	0.35	0.43
6864300	0.11	0.20	0.27	0.36	0.43	0.50
6864700	0.16	0.36	0.52	0.76	0.94	1.14
6866800	0.09	0.23	0.36	0.56	0.73	0.92
6867800	0.09	0.13	0.14	0.16	0.17	0.18
6868300	0.13	0.30	0.44	0.64	0.81	0.99
6868900	0.08	0.13	0.17	0.22	0.26	0.29
6872600	0.05	0.11	0.17	0.25	0.32	0.40
6873300	0.05	0.14	0.25	0.42	0.59	0.79
6873800	0.23	0.42	0.56	0.74	0.87	1.01
6874500	0.14	0.22	0.27	0.32	0.35	0.39
6876200	0.17	0.32	0.43	0.58	0.69	0.82
6877200	0.22	0.31	0.37	0.42	0.46	0.49
6877400	0.24	0.52	0.77	1.10	1.38	1.68
6879700	0.27	0.46	0.58	0.74	0.85	0.96
6884100	0.10	0.22	0.33	0.50	0.65	0.81
6884300	0.22	0.37	0.47	0.61	0.70	0.81
6887200	0.26	0.50	0.68	0.94	1.15	1.38
6888600	0.35	0.52	0.62	0.74	0.83	0.92
6889100	0.35	0.62	0.84	1.13	1.37	1.62
6889120	0.35	0.51	0.61	0.73	0.83	0.92
6889140	0.41	0.58	0.68	0.80	0.89	0.98
6889600	0.41	0.60	0.72	0.86	0.96	1.06
6890300	0.26	0.47	0.63	0.86	1.04	1.25
6890700	0.18	0.40	0.58	0.85	1.07	1.31
6891050	0.31	0.53	0.68	0.87	1.00	1.14
6912300	0.47	1.01	1.45	2.07	2.57	3.10
6913600	0.19	0.31	0.41	0.52	0.62	0.72
6914250	0.29	0.42	0.49	0.56	0.61	0.65
6916700	0.41	0.64	0.78	0.93	1.03	1.13
6917100	0.25	0.34	0.40	0.45	0.48	0.50
6917400	0.49	0.61	0.67	0.72	0.74	0.76

Table A.3: Rational runoff coefficients from station data (continued)

USGS station number	C2	C5	C10	C25	C50	C100
7139700	0.08	0.15	0.21	0.27	0.31	0.35
7141400	0.10	0.15	0.17	0.19	0.20	0.21
7141600	0.02	0.09	0.17	0.33	0.48	0.68
7141800	0.12	0.22	0.28	0.36	0.42	0.49
7142100	0.16	0.38	0.55	0.77	0.94	1.11
7143100	0.12	0.17	0.19	0.21	0.23	0.24
7143200	0.15	0.23	0.29	0.35	0.40	0.44
7143500	0.16	0.17	0.17	0.16	0.16	0.16
7144900	0.32	0.52	0.63	0.75	0.82	0.88
7145300	0.33	0.44	0.50	0.55	0.57	0.60
7145800	0.31	0.45	0.52	0.60	0.64	0.68
7146700	0.44	0.62	0.72	0.83	0.90	0.97
7147020	0.32	0.54	0.68	0.83	0.92	1.01
7147200	0.23	0.30	0.34	0.37	0.38	0.40
7147990	0.27	0.67	1.03	1.51	1.90	2.29
7148700	0.08	0.21	0.32	0.49	0.62	0.76
7148800	0.10	0.28	0.45	0.70	0.89	1.10
7151600	0.35	0.50	0.59	0.68	0.73	0.78
7156700	0.10	0.22	0.32	0.44	0.52	0.60
7157400	0.12	0.38	0.65	1.06	1.41	1.79
7166200	0.43	0.53	0.58	0.62	0.64	0.65
7169200	0.67	1.02	1.23	1.45	1.60	1.73
7169700	0.31	0.48	0.58	0.69	0.76	0.83
7170600	0.44	0.64	0.76	0.89	0.98	1.06
7170800	0.47	0.63	0.72	0.80	0.85	0.90
7171700	0.36	0.74	1.02	1.36	1.60	1.84
7171800	0.20	0.33	0.41	0.49	0.54	0.59
7171900	0.40	0.85	1.20	1.65	1.99	2.33
7180300	0.19	0.37	0.51	0.67	0.78	0.89
7182520	0.36	0.65	0.87	1.13	1.34	1.56
7183800	0.58	0.94	1.17	1.43	1.61	1.78
7184600	0.54	1.11	1.57	2.19	2.68	3.20

Table A.4: Physical characteristics of gaged watersheds

USGS station number	Channel length (mi)	Shape factor	Channel slope (ft/ft)	Time of concen. (hr)	Soil permeab. (in./hr)	Runoff curve number
6813700	1.908	4.06	0.0120	1.16	0.40	85
6815700	3.679	3.66	0.0045	2.47	0.37	84
6818260	7.090	3.90	0.0071	3.27	0.96	76
6846200	6.792	4.37	0.0074	3.14	1.29	73
6847600	6.580	5.53	0.0033	4.01	1.30	73
6848200	1.908	3.42	0.0094	1.25	1.30	74
6856800	5.108	6.55	0.0037	3.27	0.78	81
6863400	7.736	12.45	0.0032	4.51	1.20	72
6863700	10.663	18.65	0.0026	5.97	1.04	73
6864300	4.598	3.87	0.0046	2.84	1.08	75
6864700	9.358	9.13	0.0033	5.06	1.14	73
6866800	3.312	3.21	0.0067	2.02	1.20	72
6867800	1.429	1.90	0.0288	0.72	1.12	79
6868300	5.350	4.42	0.0062	2.84	1.19	74
6868900	5.313	9.73	0.0073	2.68	1.19	75
6872600	6.580	8.06	0.0039	3.80	1.22	73
6873300	1.858	3.93	0.0111	1.17	1.20	73
6873800	2.753	5.28	0.0091	1.62	1.17	72
6874500	18.293	12.57	0.0023	8.91	1.23	73
6876200	8.830	7.92	0.0043	4.47	0.95	76
6877200	14.142	7.60	0.0020	7.89	0.55	79
6877400	4.517	8.22	0.0054	2.66	0.46	84
6879700	10.420	8.02	0.0021	6.31	0.54	85
6884100	2.131	2.81	0.0121	1.24	1.03	82
6884300	2.647	2.42	0.0099	1.53	0.74	80
6887200	8.382	5.02	0.0072	3.64	0.40	77
6888600	8.637	4.75	0.0037	4.63	0.43	80
6889100	3.032	4.44	0.0045	2.17	0.32	85
6889120	6.468	3.97	0.0032	4.01	0.34	84
6889140	9.582	5.45	0.0026	5.56	0.36	83
6889600	4.362	4.95	0.0041	2.85	0.39	85
6890300	10.137	4.94	0.0040	5.02	0.39	73
6890700	1.348	2.16	0.0112	0.94	0.37	75
6891050	7.202	3.97	0.0068	3.36	0.78	79
6912300	3.119	2.67	0.0061	2.00	0.49	78
6913600	7.717	5.96	0.0024	4.95	0.37	83
6914250	0.907	2.24	0.0233	0.57	0.66	76
6916700	2.473	2.94	0.0075	1.60	0.90	80
6917100	1.758	3.48	0.0072	1.30	0.76	74
6917400	3.592	4.59	0.0066	2.14	0.69	77

Table A.4: Physical characteristics of gaged watersheds (continued)

USGS station number	Channel length (mi)	Shape factor	Channel slope (ft/ft)	Time of concen. (hr)	Soil permeab. (in./hr)	Runoff curve number
7139700	8.631	7.96	0.0026	5.19	1.09	73
7141400	2.019	4.72	0.0046	1.65	1.11	72
7141600	23.513	18.69	0.0019	11.10	1.13	72
7141800	14.049	11.48	0.0025	7.26	1.11	73
7142100	9.588	9.21	0.0022	5.88	1.06	73
7143100	2.610	4.63	0.0039	2.06	1.04	79
7143200	12.111	7.74	0.0022	6.86	1.04	75
7143500	10.079	4.17	0.0025	5.82	0.83	80
7144900	2.001	2.74	0.0051	1.58	2.13	74
7145300	5.810	6.67	0.0027	3.95	1.18	77
7145800	1.423	5.09	0.0092	1.04	0.68	81
7146700	9.700	9.21	0.0029	5.41	0.44	82
7147020	0.721	2.99	0.0112	0.62	0.37	84
7147200	1.411	2.26	0.0099	1.01	0.37	84
7147990	3.411	4.65	0.0096	1.83	0.49	79
7148700	3.560	2.53	0.0126	1.72	2.99	72
7148800	3.138	4.61	0.0072	1.90	1.44	78
7151600	10.538	9.48	0.0040	5.14	1.88	74
7156700	4.350	4.70	0.0073	2.35	1.90	73
7157400	6.549	6.38	0.0074	3.07	1.03	73
7166200	5.878	5.07	0.0038	3.56	0.66	81
7169200	4.418	2.59	0.0057	2.58	0.39	79
7169700	2.299	2.93	0.0088	1.45	0.32	78
7170600	6.847	3.13	0.0034	4.08	0.85	78
7170800	3.362	2.64	0.0050	2.25	0.95	80
7171700	3.231	3.38	0.0090	1.80	0.51	79
7171800	1.429	3.81	0.0314	0.70	0.51	81
7171900	10.048	5.24	0.0041	4.94	0.56	78
7180300	1.479	3.78	0.0090	1.08	0.68	79
7182520	6.879	5.72	0.0023	4.66	0.47	82
7183800	5.748	2.52	0.0034	3.64	0.99	81
7184600	8.780	2.83	0.0017	6.01	1.23	81

Table A.5: Climatic characteristics of gaged watersheds

USGS station number	Mean annual precipitation (in.)	Mean annual lake evaporation (in.)	Mean ann. precipitation deficit (in.)
6813700	34.0	44.7	10.7
6815700	35.9	43.6	7.7
6818260	37.0	43.5	6.5
6846200	20.5	55.6	35.1
6847600	19.5	58.3	38.8
6848200	22.4	54.6	32.2
6856800	31.4	48.4	17.0
6863400	21.7	59.7	38.0
6863700	23.3	58.2	34.9
6864300	25.9	55.4	29.5
6864700	27.4	54.2	26.8
6866800	21.0	60.2	39.2
6867800	25.4	55.5	30.1
6868300	25.1	54.7	29.6
6868900	27.3	53.4	26.1
6872600	25.3	52.3	27.0
6873300	23.0	55.7	32.7
6873800	24.5	54.5	30.0
6874500	26.6	52.0	25.4
6876200	29.2	50.5	21.3
6877200	32.0	51.0	19.0
6877400	32.0	51.1	19.1
6879700	32.1	48.1	16.0
6884100	30.1	47.5	17.4
6884300	30.9	46.9	16.0
6887200	33.3	47.4	14.1
6888600	35.3	46.7	11.4
6889100	34.7	44.8	10.1
6889120	34.7	45.1	10.4
6889140	34.8	45.1	10.3
6889600	36.4	46.1	9.7
6890300	34.9	44.7	9.8
6890700	37.4	44.6	7.2
6891050	37.5	44.9	7.4
6912300	36.8	46.6	9.8
6913600	38.3	45.7	7.4
6914250	39.3	46.2	6.9
6916700	40.0	46.2	6.2
6917100	40.6	45.9	5.3
6917400	41.6	45.2	3.6

Table A.5: Climatic characteristics of gaged watersheds (continued)

USGS station number	Mean annual precipitation (in.)	Mean annual lake evaporation (in.)	Mean ann. precipitation deficit (in.)
7139700	22.0	66.6	44.6
7141400	20.4	65.9	45.5
7141600	21.4	63.6	42.2
7141800	22.9	60.8	37.9
7142100	23.8	62.9	39.1
7143100	26.1	55.9	29.8
7143200	26.5	55.2	28.7
7143500	27.7	54.5	26.8
7144900	25.8	58.5	32.7
7145300	30.5	53.9	23.4
7145800	32.3	53.1	20.8
7146700	33.8	51.4	17.6
7147020	33.1	51.8	18.7
7147200	33.3	51.8	18.5
7147990	35.4	50.9	15.5
7148700	25.5	59.3	33.8
7148800	26.5	58.0	31.5
7151600	28.7	55.7	27.0
7156700	19.1	68.7	49.6
7157400	21.0	67.5	46.5
7166200	38.3	48.4	10.1
7169200	36.5	49.8	13.3
7169700	36.9	49.7	12.8
7170600	40.4	47.7	7.3
7170800	40.6	47.2	6.6
7171700	36.2	50.2	14.0
7171800	35.7	50.8	15.1
7171900	36.4	50.1	13.7
7180300	33.2	50.9	17.7
7182520	37.9	47.7	9.8
7183800	42.3	45.4	3.1
7184600	42.6	45.4	2.8

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