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Updated Regional Flood Frequency Equations for Small, Rural, Unregulated Watersheds in Kansas

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This report presents one set of regional regression equations to replace both the Extended Rational Method and Three Variable Regression Methods. The Extended Rational and the Three Variable Regression equations have the same three inputs: drainage area, mean annual precipitation, and rainfall intensity. The two sets of equations produce very similar results.

The equations presented in this report incorporate current rainfall frequency and mean annual precipitation data, as well as current flood frequency estimates, and were developed using the best available regional regression techniques. The authors recommend adoption of these equations in subsequent editions of the KDOT *Design Manual.*

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Final Report

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Abstract

This report presents new regional flood frequency equations intended to replace the Extended Rational and Three Variable Regression equations introduced in K-TRAN: KU-06-4, *Flood Frequency Relationships for Small Watersheds in Kansas* (McEnroe, Young, & Rome, 2007). This update was necessitated by the publication of new National Weather Service (NWS) rainfall frequency estimates for the Midwest in *NOAA Atlas 14 Volume 8* (Perica et al., 2013).

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The equations presented in this report incorporate current rainfall frequency and mean annual precipitation data, as well as current flood frequency estimates, and were developed using the best available regional regression techniques. The authors recommend adoption of these equations in subsequent editions of the KDOT *Design Manual.*

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Chapter 1: Introduction

1.1 Background

The purpose of this study is to update K-TRAN: KU-06-4, *Flood Frequency Relationships for Small Watersheds in Kansas* to account for new rainfall frequency estimates and additional flood data. McEnroe, Young, and Rome (2007) provided two sets of statewide flood-frequency equations for watersheds with contributing drainage areas under 30 mi^2: one based on the form of rational method (the Extended Rational Method) and one based on regional regression method both for drainage areas under 30 mi^2 (the Three-Variable Regression Method). Both methods are included in the KDOT (2011) *Design Manual*.

In 2013, the National Weather Service (NWS) Hydrometeorological Design Studies Center released *NOAA Atlas 14 Volume 8*, which presents the first revision of rainfall frequency estimates for the Midwest since 1977 (Perica et al., 2013). McEnroe and Young (2014) developed new county-based rainfall frequency tables for KDOT based on *NOAA Atlas 14*. These rainfall tables will replace those developed by McEnroe (1997).

Both the Extended Rational Method and the Three Variable Regression Method were calibrated to the McEnroe (1997) rainfall tables. With the release of *NOAA Atlas 14*, it is important to revise hydrologic methods to account for the current rainfall frequency estimates. Recalibration at this time allows the inclusion of additional flood gage data.

This report presents one set of regional regression equations to replace both the Extended Rational Method and Three Variable Regression Methods. The Extended Rational and the Three Variable Regression equations have the same three inputs: drainage area, mean annual precipitation, and rainfall intensity. The two sets of equations produce very similar results. Using one set of equations will simplify analysis and reduce possible confusion without compromising accuracy.

Because this report serves as an update of McEnroe et al. (2007), some sections of the text and some figures from that report are reproduced in this report.

Chapter 2: Data for Regional Regression Analyses

2.1 Selection of United States Geological Survey Stream-Gaging Records

The data set for this report included 91 United States Geological Survey (USGS) streamflow-gaging stations in Kansas. The selected stations meet the following conditions:

- Drainage area under 30 mi^2
- Record length of 10 years or more (through water year 2014)
- Unregulated stream
- Rural watershed
- Well-defined watershed boundary; no apparent non-contributing areas

The criteria above are the same as those used in McEnroe et al. (2007) with one exception: the minimum record length for this study is 10 years instead of 20 years. As a result of this change, 19 more stations were included in this report. The statistical methods used in this report account for record length and uncertainty in flood frequency analysis; including more stations (even those with shorter records) improves the accuracy of the regional flood frequency analysis.

Ninety-seven stations from the USGS database met the first three criteria listed above. Six of these stations were excluded because of urbanization or missing data. The excluded stations are 6818260, White Clay Creek at Atchison; 6891650, Naismith Creek at Lawrence; 6892800, Turkey Creek at Merriam; 7144320, Gypsum Creek at Gilbert Street Wichita; 7144330, Dry Creek at Lincoln Street Wichita; and 6845900, Little Beaver Creek tributary near McDonald. Table A.1 lists the ID numbers, names, drainage areas and record lengths for the 91 retained stations. Figure 2.1 shows the locations of these stations.

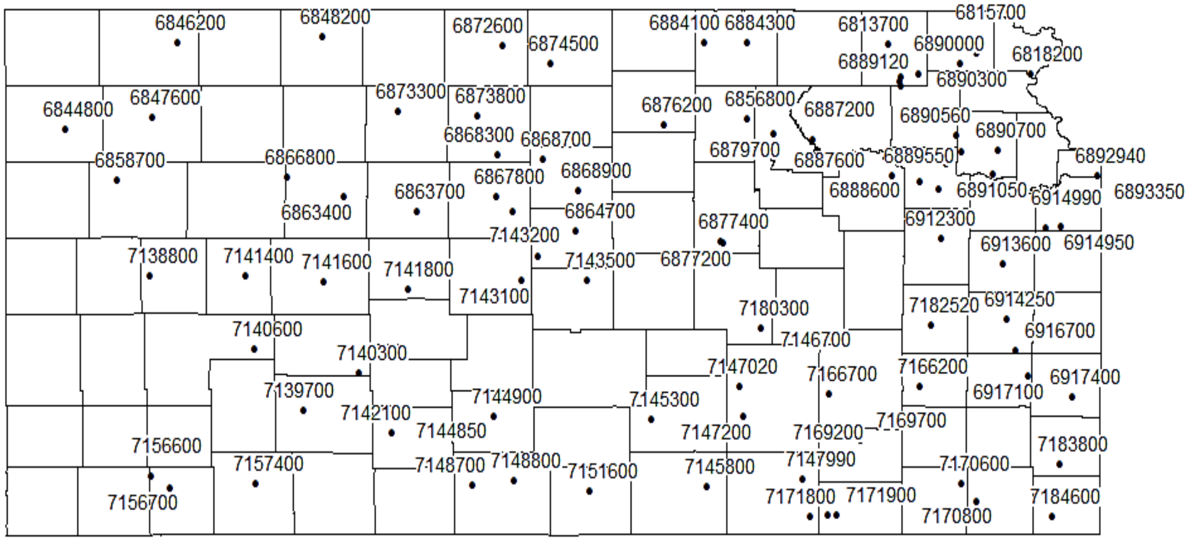

Figure 2.1: Locations of Selected USGS Streamflow-Gaging Stations

2.2 Definitions for Flood Frequency

The terms recurrence interval and return period are often used to describe the frequency of extreme flood events. These terms can be interpreted in two different ways:

- The average period of time between independent events that equal or exceed a specified magnitude, or
- The reciprocal of the annual exceedance probability (AEP, which is the probability that at least one event greater than or equal to a specified magnitude will occur in any given year).

The difference between these two definitions is minor for very large events (return periods greater than 10 years); however, the difference becomes significant for more frequent events.

For the sake of clarity, this report uses the term return period to refer to the reciprocal of the AEP. In this report Q_T denotes the peak flow for a flood with an annual exceedance probability of 1/T. KDOT has historically used this definition of return period to express flood frequencies. The McEnroe, Young, Williams, and Hinshaw (2013) rainfall tables present rainfall depths and intensities in terms of the Average Recurrence Interval (ARI). As such, rainfall intensities in this report are denoted as i_{ARI}. The ARI is not equal to 1/AEP.

Table 2.1: Definitions of Rainfall and Flood Frequency as Used in this Report

Symbol	Term	Definition
ARI	Average Recurrence Interval	The average period of time between independent events that equal or exceed a specified magnitude.
AEP	Annual Exceedance Probability	The probability that a location will experience one or more events that equal or exceed a specified magnitude in any given year.
T	Return Period	The reciprocal of the annual probability of exceedance, T = 1/AEP.
Q_T	Flood Quantile	The instantaneous peak discharge with an annual exceedance probability, AEP, equal to 1/T.

2.3 Flood Frequency Analysis

We performed a flood-frequency analysis for each station using the U.S. Army Corps of Engineers Hydraulic Engineering Center Statistical Software Package (HEC-SSP; Brunner & Fleming, 2010). HEC-SSP predicts flood frequency by the Bulletin 17B method from *Guidelines for Determining Flood Flow Frequency* (Interagency Advisory Committee on Water Data, 1981). A regression equation for Kansas was used to obtain the generalized skew coefficient for each station (Rasmussen & Perry, 2000). Table A.2 lists the resulting discharges for return periods of 2, 5, 10, 25, 50, and 100 years (AEP = 0.5, 0.2, 0.1, 0.04, 0.02, and 0.01).

2.4 Watershed Characteristics

This section lists the physical and climatic characteristics considered in the regression analysis. Based on experience gained with regional frequency analysis in Kansas, this study limited the potential independent variables to mean annual rainfall, rainfall intensity, and drainage area (McEnroe et al., 2007, 2013). The selection of rainfall intensity requires the estimation of time of concentration, which is computed using channel length and slope. The variables listed below are explained in Sections 2.4.1 through 2.4.6. Tables A.3 and A.4 list the values of these variables for the 91 gaged watersheds.

A = drainage area (mi^2)
L = length of main channel, extended to the drainage divide (ft)
Sl = average slope of main channel, defined as the elevation difference of two points located 10% and 85% of the channel length from the outlet to the drainage divide, divided by the length between the two points (ft/ft)
MAP = mean annual precipitation (in.) from 1981 to 2010 climate normals map (Figure 2.2)
tc = time of concentration (min)
IaARI (tc) = basin-average rainfall intensity (in./hr) for average recurrence interval (ARI) and duration tc (min)

2.4.1 Drainage Area, Channel Length, and Average Channel Slope

Watershed area (A), channel length (L), and channel slope (Sl) were all obtained from *Estimating the Discharge for Ordinary High Water Levels in Kansas*. Young, McEnroe, Gamarra, Luo, and Lurtz (2014) used ArcHydro 2.0 in ArcGIS 10.0 (Djokic, 2008) to determine these three characteristics for each USGS site. Each watershed was delineated using three arc-second digital elevation models (DEMs) developed and distributed by the USGS as part of the National Elevation Dataset (NED; Gesch, 2007; Gesch et al., 2002). All watersheds were delineated using DEMs of the same resolution, even if higher-resolution DEMs were available in some areas. It is important to use a consistent resolution for analysis, as channel length invariably increases (and slope decreases) with increasing resolution. For the purpose of regional analysis, consistency in the dataset is crucial. All DEMs were projected into a Universal Transverse Mercator (UTM) map projection (Zone 13-15 depending on longitude) based on the North American Datum of 1983 (NAD83) prior to analysis in ArcHydro.

The physical characteristics of the watershed are listed in Table A.3. The drainage areas range from 0.18 mi^2 to 29.6 mi^2, the channel lengths range from 5,330 ft to 123,000 ft, and the average channel slopes range from 0.00158 ft/ft to 0.0284 ft/ft.

2.4.2 Mean Annual Precipitation

Mean annual precipitation (MAP) is commonly defined using a 30-year average of station data. Prior regression equations for Kansas used the MAP contours published in Rasmussen and Perry (2000) based on meteorological data from 1961 to 1990. This study uses the current Mean Annual Precipitation Map (1981-2010) produced by the Weather Data Library in the Department of Agronomy at Kansas State University. The MAP value for each watershed was interpolated from the map in Figure 2.2. MAP values for the selected watersheds range from 18.9 to 45.2 inches.

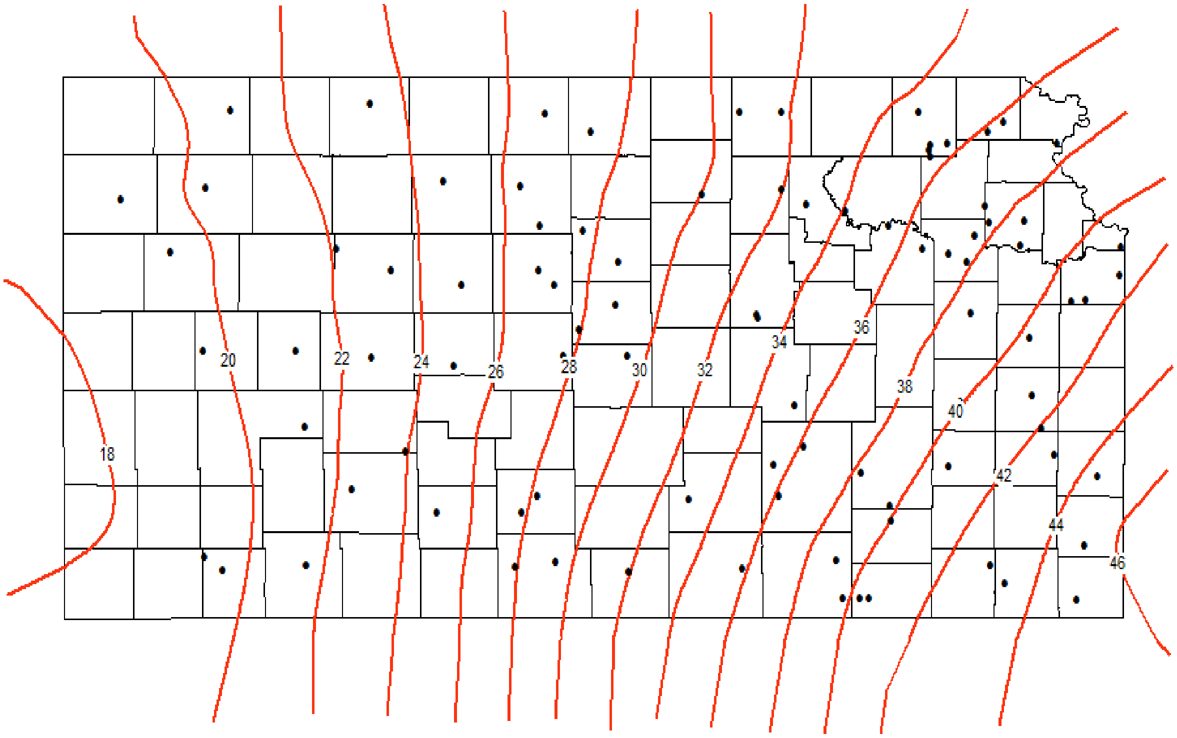

Figure 2.2: Mean Annual Precipitation (Inches) Based on 1981-2010 Climate Normal

Produced by the Weather Data Library, Department of Agronomy, Kansas State University from 1981 to 2010 climate normals (Kansas Office of the State Climatologist, 2015).

NOTE: It is important to use the correct MAP data for each set of regression equations. McEnroe et al. (2007) and Rasmussen and Perry (2000) both use MAP from 1961 to 1990 climate normals.

2.4.3 Time of Concentration

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

$$t_c = 0.0368 \left(\frac{L}{\sqrt{Sl}}\right)^{0.66}$$ **Equation 2.1**

Where:

t_c = time of concentration (min)

L = length of the longest flow path (ft)

Sl = slope, measured between points 10% and 85% from outlet to drainage divide (ft/ft)

Times of concentration for the watersheds range from 37.8 minutes to 648 minutes.

2.4.4 Rainfall Intensity

KDOT'S rainfall tables for counties in Kansas (McEnroe & Young, 2014) were updated in 2013 to reflect *NOAA Atlas 14 Volume 8* (Perica et al., 2013). These new rainfall tables were used to determine point-rainfall intensity for duration equal to the time for concentration and for average recurrence intervals of 2, 5, 10, 25, 50, and 100 years. When a watershed is larger than a few hundred acres, the relevant rainfall intensity for hydrologic analyses is the basin-average rainfall intensity, rather than the point-rainfall intensity. Basin-averaged intensity is described and explained in the report *Flood Frequency Relationships for Small Watershed in Kansas* (McEnroe et al., 2007). The relationship is described by the equation:

$$\mathrm{Ia}_{ARI}(\mathrm{D}) = \mathrm{Ip}_{ARI}(\mathrm{D}) \cdot \left[1 - \mathrm{BV} \cdot (1 - e^{-0.015 \cdot A})\right]$$ **Equation 2.2**

$$\mathrm{BV} = 0.355 \cdot D^{-0.428}$$ **Equation 2.3**

Where:

Ia_{ARI} (D) = basin-average rainfall intensity for duration, D, and average recurrence interval, ARI

Ip_{ARI} (D) = point rainfall intensity for duration, D, and average recurrence interval, ARI

A = drainage area (mi^2)

BV = maximum reduction of point rainfall, varies with duration

D = duration of rainfall event, set equal to t_c (in hours)

ARI = average recurrence interval (years)

Chapter 3: Regional Regression Analyses

3.1 USGS Weighted-Multiple-Linear Regression Program

The regional flood frequency (RFF) analyses in this study were performed using Generalized Least Squares (GLS) regression with the Weighted-Multiple-Linear Regression Program (WREG 1.05; Eng, Chen, & Kiang, 2009) developed by the United States Geological Survey (USGS). GLS, introduced by Stedinger and Tasker (1985), takes record lengths and temporal and spatial correlations between gage records into account. It is considered by USGS to be the best method currently available for RFF analysis. The use of GLS here represents a significant improvement over the analysis in McEnroe et al. (2007).

3.2 Examination of Predictor Variables

Regression analyses were performed on the base-10 logarithms of the flood discharges and watershed characteristics. Figure 3.1 shows the heteroscedasticity in the relationship between Q_{25} and drainage area, the most important predictor variable, demonstrating the importance of using log-transformed data. Figure 3.2 shows that the relationship between $\log(Q_{25})$ and $\log(A)$ is more nearly homoscedastic.

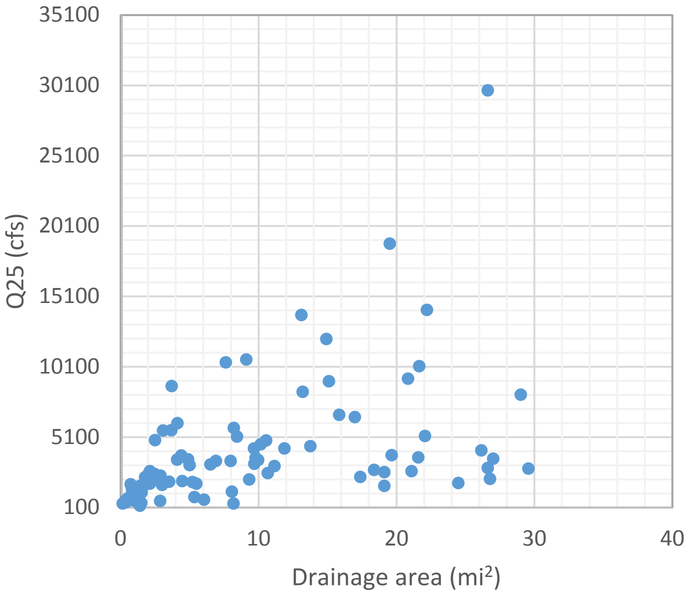

Figure 3.1: Scatter Plot for Q_{25} and Drainage Area

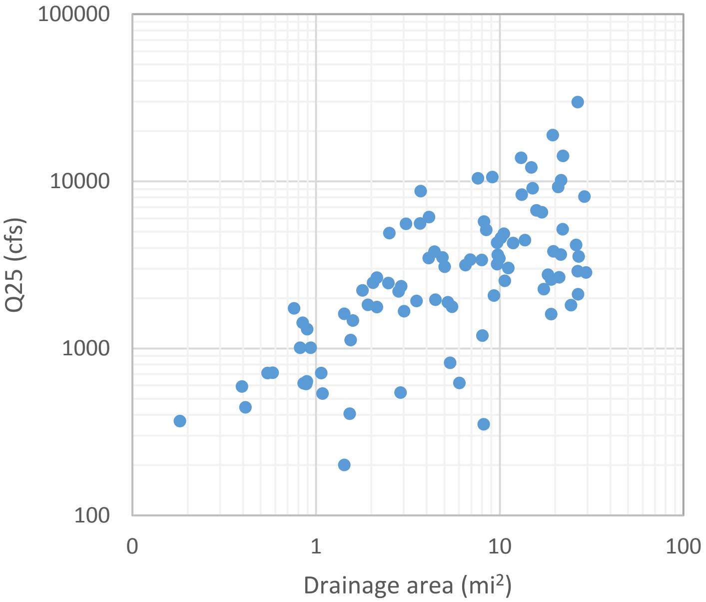

Figure 3.2: Scatter Plot for Logarithms of Q_{25} and Drainage Area

Tables 3.1 through 3.3 show the correlation matrices for the logarithms of the flood discharges and selected potential independent variables for return periods of 2, 25, and 100 years (AEP of 0.5, 0.04, and 0.01). McEnroe et al. (2007) demonstrated that the product of drainage area and basin-average rainfall intensity is a strong predictor of flood quantiles. Tables 3.1 through 3.3 all show that the product of basin-average rainfall intensity and drainage area has the highest correlation with flood discharge. In addition, $Ia_{ARI} \cdot A$ has a very low correlation with mean annual precipitation.

Table 3.1: Correlation Matrix for Logarithms of Q_2 (AEP = 0.5) and Possible Explanatory Variables

	Q_2	A	Ia_2	MAP	Ia_2A
Q_2	1.00				
A	0.50	1.00			
Ia_2	-0.28	-0.72	1.00		
MAP	0.59	-0.05	0.33	1.00	
Ia_2A	0.77	0.89	-0.63	0.24	1.00

Table 3.2: Correlation Matrix for Logarithms of Q_{25} (AEP = 0.04) and Possible Explanatory Variables

	Q_{25}	A	Ia_{25}	MAP	$Ia_{25}A$
Q_{25}	1.00				
A	0.47	1.00			
Ia_{25}	-0.30	-0.74	1.00		
MAP	0.45	-0.05	0.30	1.00	
$Ia_{25}A$	0.69	0.90	-0.67	0.20	1.00

Table 3.3: Correlation Matrix for Logarithms of Q_{100} (AEP = 0.01) and Possible Explanatory Variables

	Q_{100}	A	Ia_{100}	MAP	$Ia_{100}A$
Q_{100}	1.00				
A	0.46	1.00			
Ia_{100}	-0.31	-0.75	1.00		
MAP	0.38	-0.05	0.30	1.00	
$Ia_{100}A$	0.65	0.90	-0.68	0.19	1.00

3.3 USGS WREG Procedure

Weighted-multiple-linear regression (WREG) is a software package developed by the USGS for regional flood frequency analysis. WREG offers several methods for RFF, including ordinary least squares (OLS), weighted least squares (WLS), and generalized least squares (GLS). GLS is considered the best available method. Application of GLS using WREG is outlined in USGS's *User's Guide to the Weighted-Multiple-Linear Regression Program, WREG Version 1.0* (Eng et al., 2009).

The required input to WREG includes watershed characteristics for each watershed (to be used as independent variables), the flood quantile estimates for each gage (to be used as dependent variables), the weighted skew coefficient and log-Pearson Type III frequency factors (K values) used in the flood frequency analyses, and the time series of the annual maxima for each site.

Based on experience gained in McEnroe et al. (2007) and other studies, we focused our analysis on using GLS within WREG to develop equations relating the $\log(Q_T)$ to the log-transformed dependent variables MAP and $Ia_{ARI} \cdot A$. This combination of independent variables has shown to be the best for predicting flood quantiles in Kansas.

For GLS, the user must fit a correlation model to describe the spatial correlation in annual peak discharges. The correlation model has two parameters, α and θ. WREG plots a sample correlation using all data with records that equal or exceed a specified length. In this report, the number of concurrent years was set to 15. The correlation model was fit using $\alpha = 0.0001$ and $\theta = 0.0985$.

The final regression equations for the flood quantiles are presented in Table 3.4.

Table 3.4: Three-Variable Regression Equations for Flood Discharge

Annual Exceedance Probablity	Equation	Standard error of estimate	
		log units	%
0.5	$Q_2 = 0.0105 \cdot MAP^{2.720} \cdot (Ia_2 \cdot A)^{1.000}$	0.215	+64%, -39%
0.2	$Q_5 = 0.269 \cdot MAP^{1.968} \cdot (Ia_5 \cdot A)^{1.002}$	0.186	+53%, -35%
0.1	$Q_{10} = 1.12 \cdot MAP^{1.636} \cdot (Ia_{10} \cdot A)^{1.004}$	0.195	+57%, -36%
0.04	$Q_{25} = 4.47 \cdot MAP^{1.310} \cdot (Ia_{25} \cdot A)^{1.004}$	0.218	+65%, -39%
0.02	$Q_{50} = 9.77 \cdot MAP^{1.120} \cdot (Ia_{50} \cdot A)^{1.004}$	0.237	+73%, -42%
0.01	$Q_{100} = 19.1 \cdot MAP^{0.959} \cdot (Ia_{100} \cdot A)^{1.005}$	0.257	+81%, -45%

Note: Applicable to unregulated rural streams with drainage areas under 30 mi^2 in Kansas.
Units: Q in cfs, MAP in inches, Ia_{ARI} in in./hr, A in mi^2

3.4 Evaluation and Comparison of the New Equations

The standard errors reported in Table 3.4 are larger than those reported in McEnroe et al. (2007). The difference is due to the statistical methodology used in this report; GLS standard errors cannot be directly compared to those from an analysis using basic multiple linear regression (MLR). GLS is a sophisticated statistical technique that accounts for varying station record lengths and the spatial correlation and temporal overlap of gages in the regional analysis. Regional flood frequency analysis performed using GLS will produce more accurate and reliable regression equations than MLR.

Figures 3.3 through 3.8 compare estimated streamflow versus observed streamflow using the new three-variable regression equation, the old three-variable regression equation regression equation, and the USGS two-variable regression equation. The results for the extended rational method are not presented as they are very similar to the results for the old three-variable equations.

Figures 3.9 through 3.14 present a comparison of the old three-variable equation results with the results of the three-variable equation developed in this study. The old three-variable equation consistently over-predicts higher flood discharges at each recurrence interval and under-predicts lower flood discharges for all but the 2-year event.

Judging from the results plotted in these figures, the USGS equations overstate flood discharge when used with the new *NOAA Atlas 14 Volume 8* (Perica et al., 2013) rainfall intensities and the new MAP estimates for Kansas. This overestimation is particularly evident for watersheds with lower peak flows. Figure 3.3 shows that the USGS equations overestimate peak discharge for nearly all of the watersheds with Q_2 less than a few hundred cfs, where uncertainty in estimation is generally higher. Results compared to the old three-variable regression equation are mixed. In some cases (e.g., low return period, low flow) the older equation appears to over predict flood discharge. In other cases (particularly for high return periods, low discharge) the older equations produce lower estimates of peak flow.

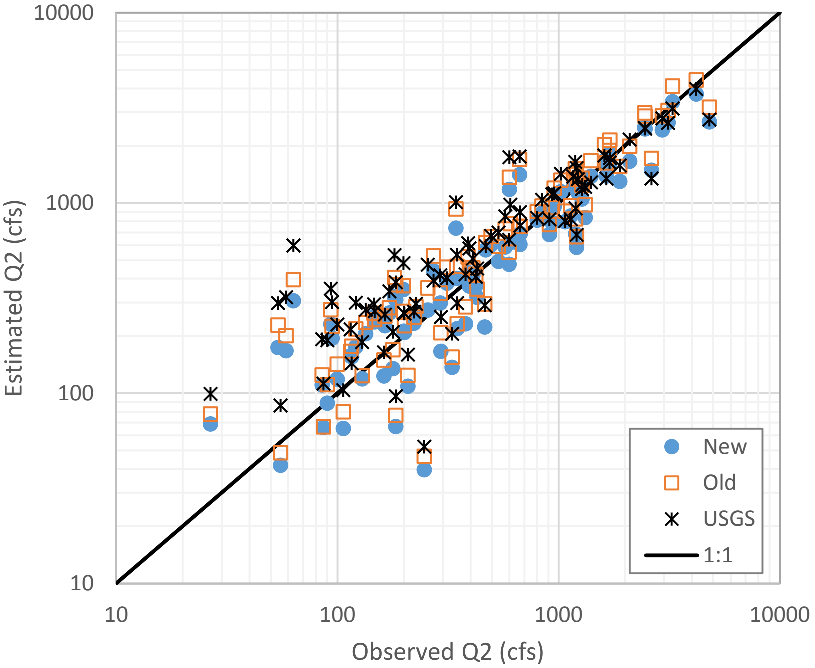

Figure 3.3: Scatter Plot to Determine Discharge Accuracy for Q_2 (AEP = 0.5) Using Various Equations

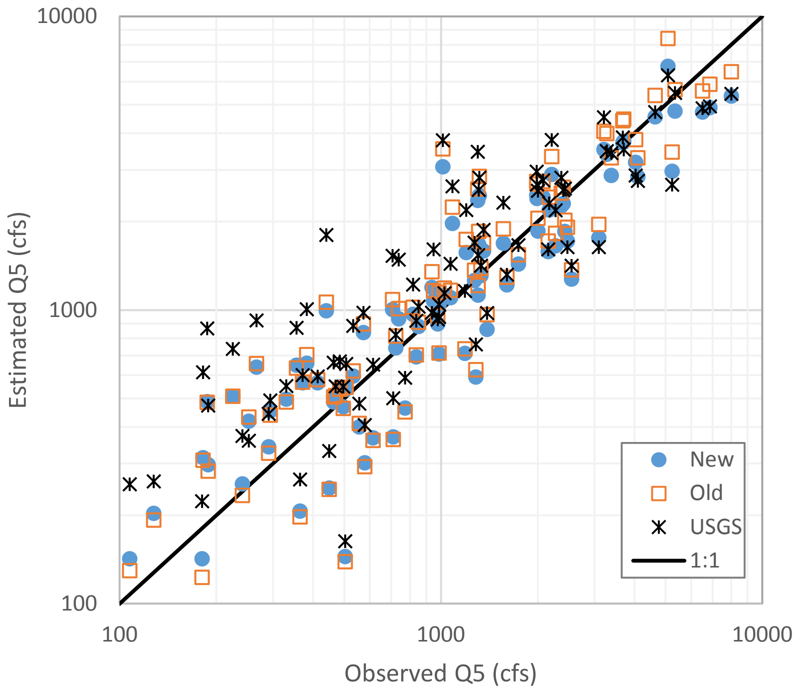

Figure 3.4: Scatter Plot to Determine Discharge Accuracy for Q_5 (AEP = 0.2) Using Various Equations

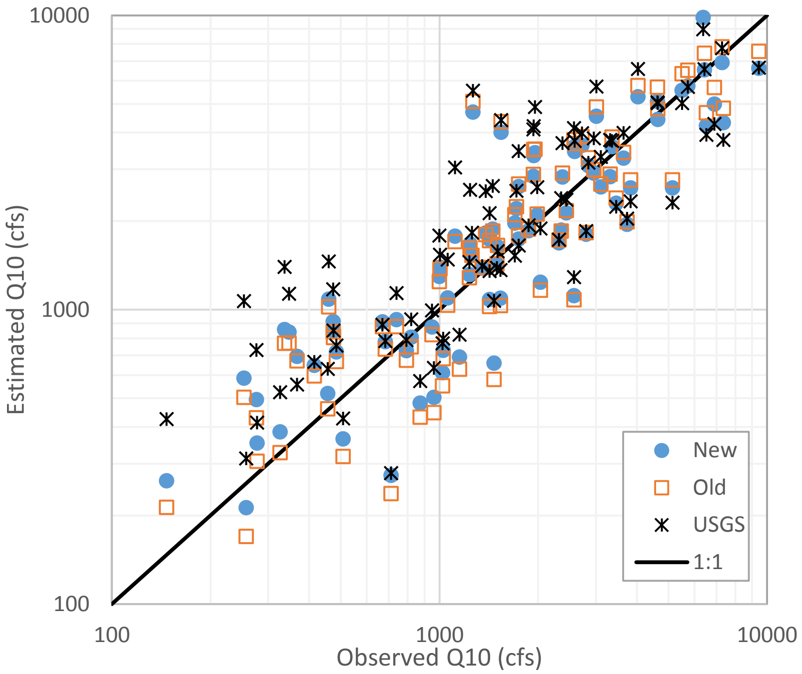

Figure 3.5: Scatter Plot to Determine Discharge Accuracy for Q_{10} (AEP = 0.1) Using Various Equations

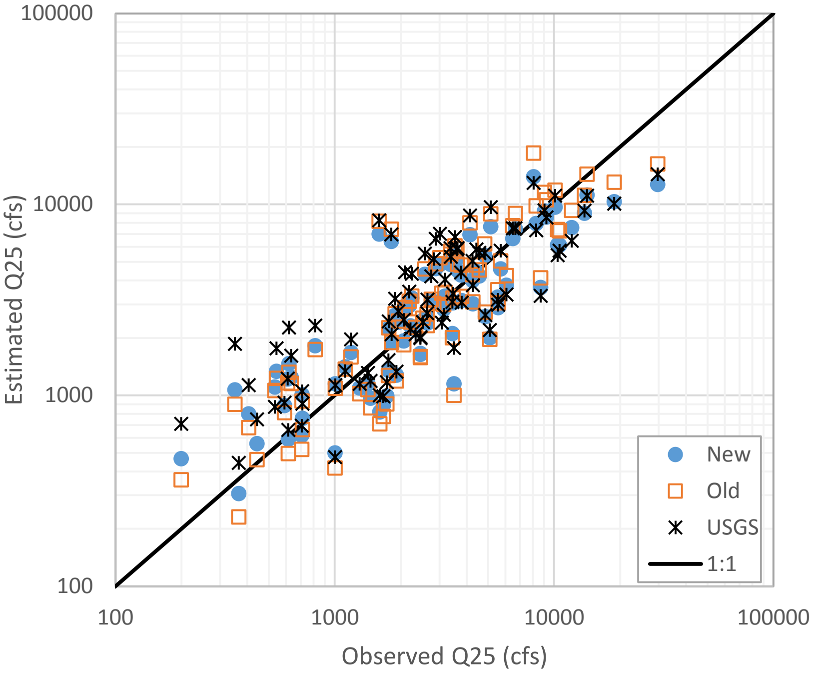

Figure 3.6: Scatter Plot to Determine Discharge Accuracy for Q_{25} (AEP = 0.04) Using Various Equations

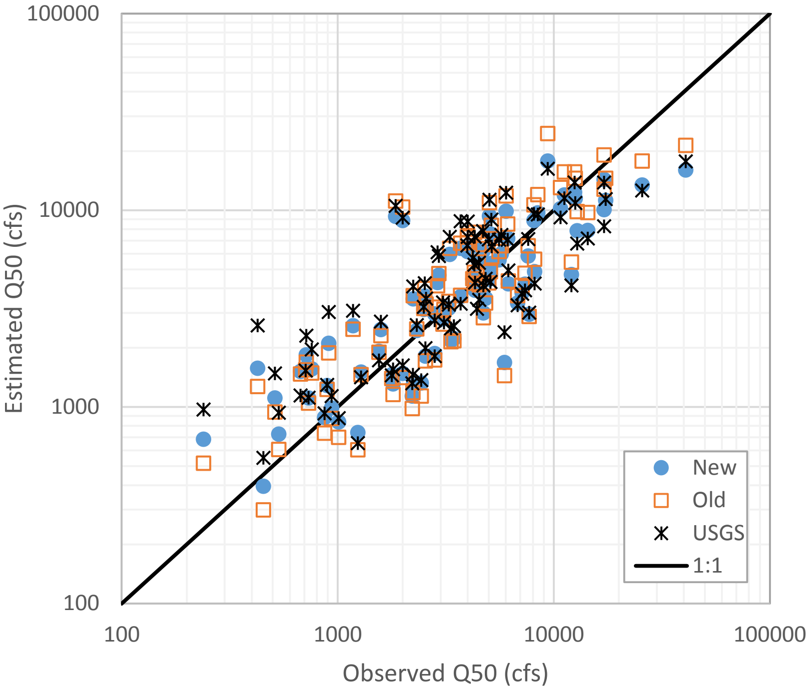

Figure 3.7: Scatter Plot to Determine Discharge Accuracy for Q_{50} (AEP = 0.02) Using Various Equations

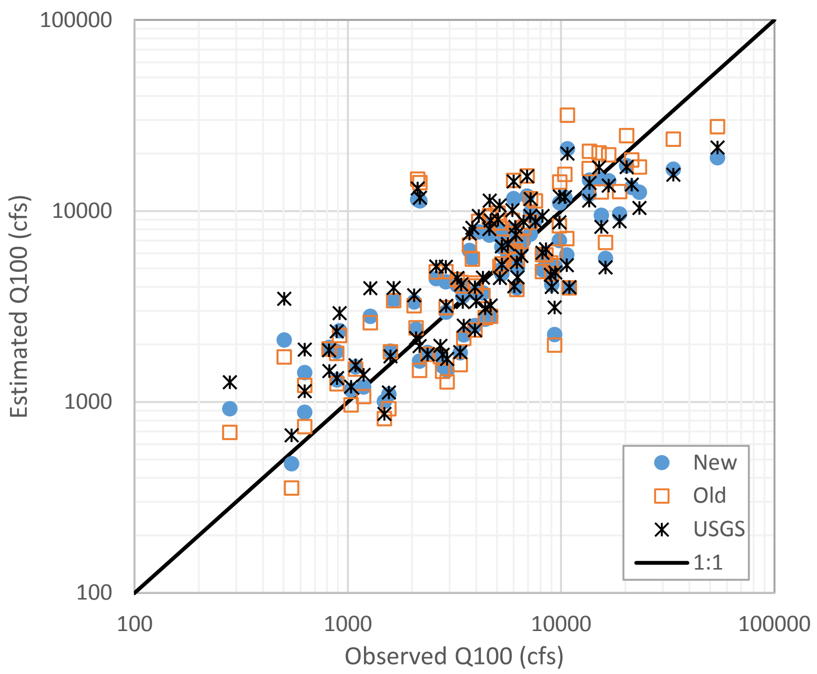

Figure 3.8: Scatter Plot to Determine Discharge Accuracy for Q_{100} (AEP = 0.01) Using Various Equations

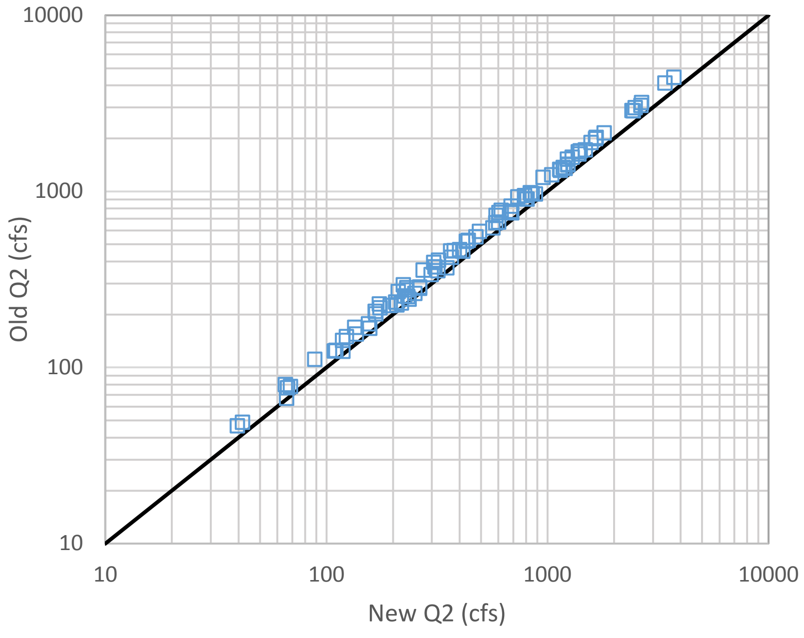

Figure 3.9: Comparison of Old to New Three-Variable Equation Results for Q_2 (AEP = 0.5)

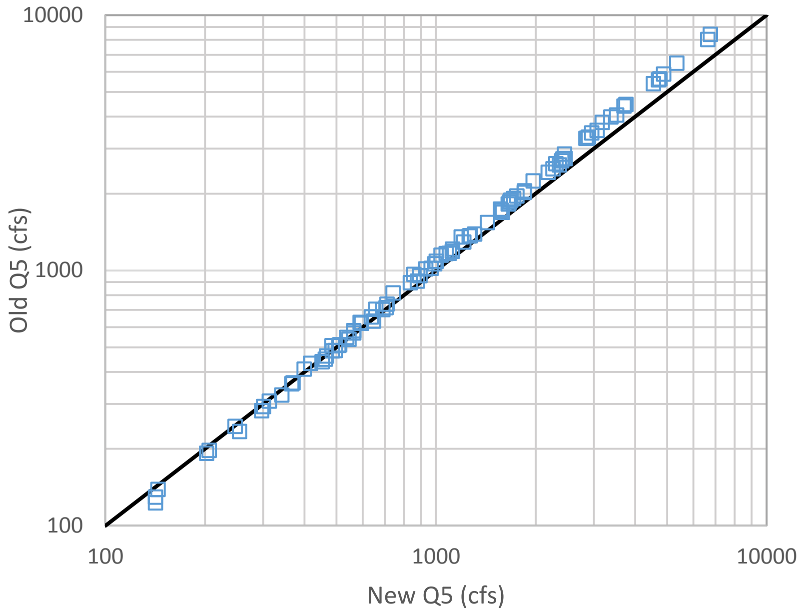

Figure 3.10: Comparison of Old to New Three-Variable Equation Results for Q_5 (AEP = 0.2)

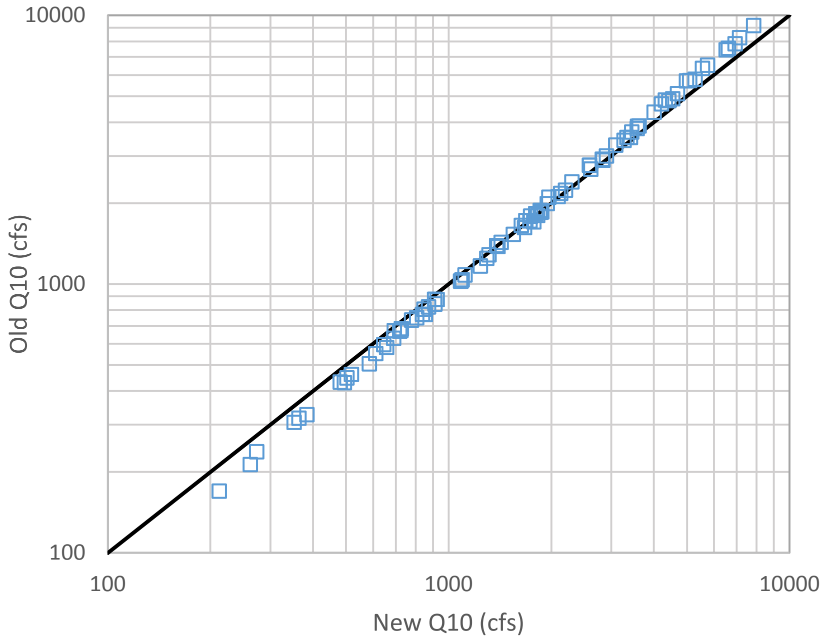

Figure 3.11: Comparison of Old to New Three-Variable Equation Results for Q_{10} (AEP = 0.1)

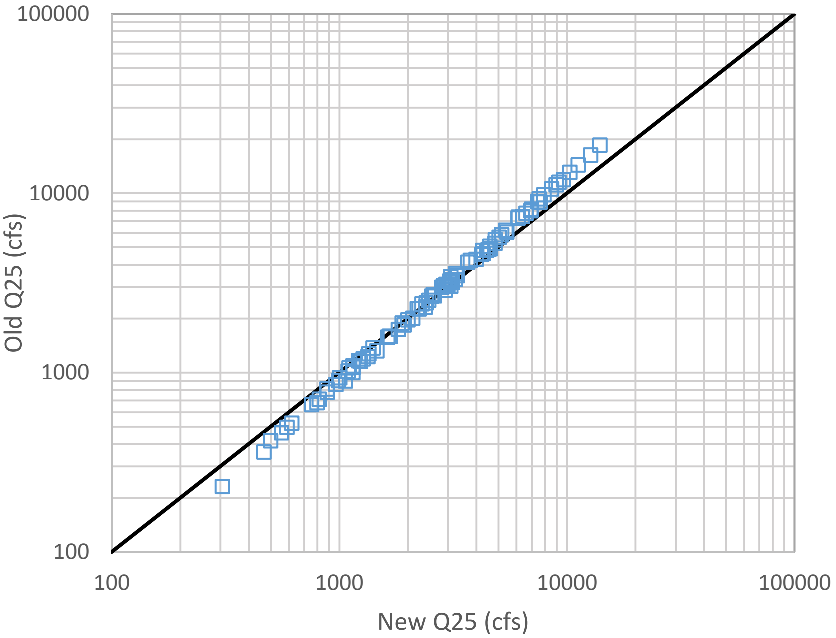

Figure 3.12: Comparison of Old to New Three-Variable Equation Results for Q_{25} (AEP = 0.04)

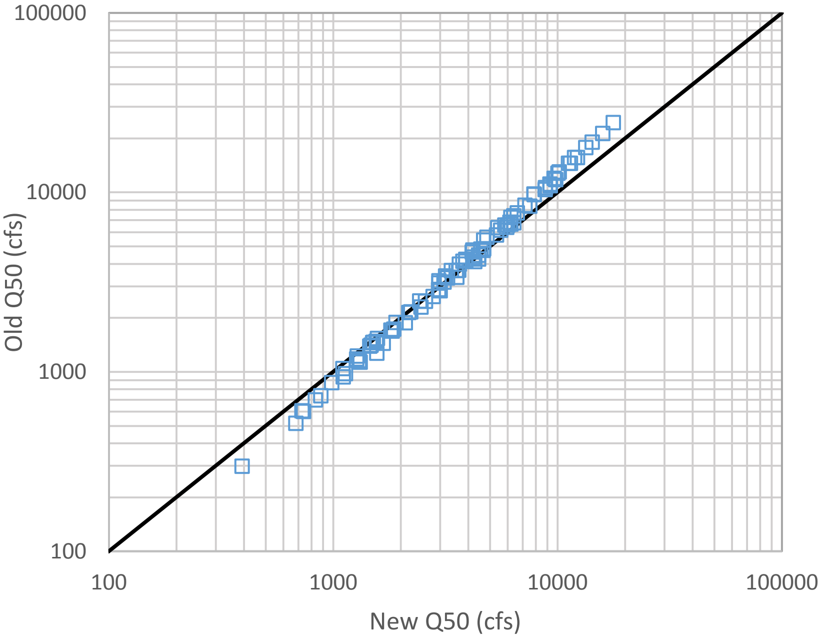

Figure 3.13: Comparison of Old to New Three-Variable Equation Results for Q_{50} (AEP = 0.02)

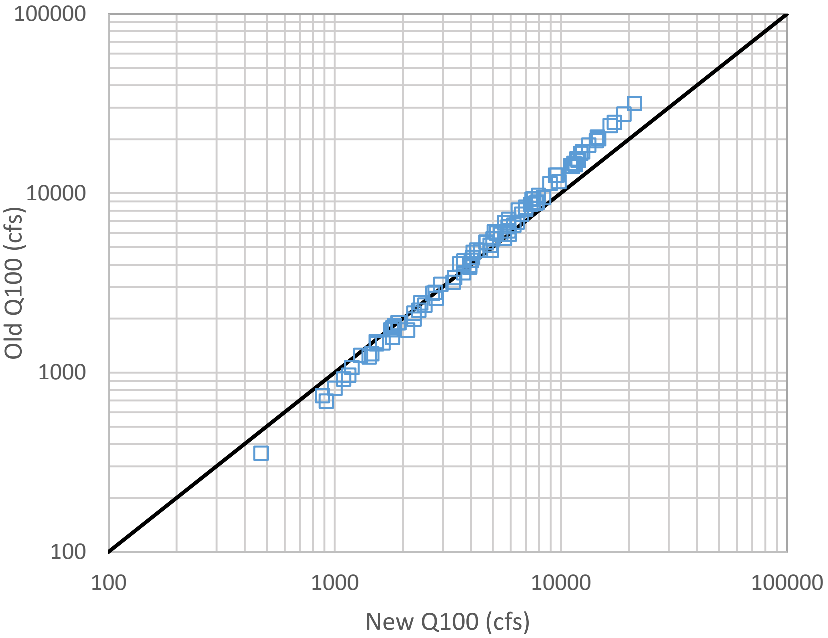

Figure 3.14: Comparison of Old to New Three-Variable Equation Results for Q_{100} (AEP = 0.01)

Chapter 4: Conclusions

This report presents regional regression equations for the prediction of flood quantiles for small (under 30 mi^2), unregulated, rural watersheds in Kansas in Table 3.4. These equations are intended to replace the Extended Rational Method and Three Variable Regression Method in subsequent releases of the KDOT *Design Manual*.

The equations in Table 3.4 incorporate new estimates of the mean annual precipitation and rainfall intensities and have been calibrated to the newly released *NOAA Atlas 14 Volume 8* (Perica et al., 2013). These equations incorporate information from an additional 10 years of peak-flow data for active stations.

Chapter 5: Application

5.1 Step-by-Step Procedure

The three-variable regression equations in Table 3.4 are applicable to unregulated streams with rural watersheds smaller than 30 mi^2 in Kansas. To estimate the T-year discharge with one of these equations, follow the steps below.

1. Determine the watershed drainage area, main channel length, and channel slope, preferably using automated delineation in GIS using a three arc-second DEM. If automated delineation in GIS is not used:
    a. Delineate the watershed boundary on a USGS topographic map.
    b. Measure the drainage area, A, in mi^2.
    c. Identify the main channel on the topographic map and extend it upstream to the watershed divide (perpendicular to the elevation contours).
    d. Measure the length of the main channel, L, in feet, following the twists and turns.
    e. Identify points along the channel at 10% and 85% of L upstream of the watershed outlet.
    f. Determine the elevations at these two points.
    g. 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).
2. Compute the time of concentration, t_c, in minutes with Equation 2.1.
3. Locate KDOT's rainfall intensity table (McEnroe & Young, 2014) for the county that contains the centroid of the watershed. Look up the rainfall intensity for the desired recurrence interval and duration equal to the time of concentration. Interpolate linearly for duration as needed. Make sure that the rainfall intensity table is based on the *NOAA Atlas 14 Volume 8* (Perica et al., 2013) precipitation frequency atlas.
4. Compute the corresponding basin-average rainfall intensity with Equations 2.2 and 2.3.
5. Locate the centroid of the watershed on the map of mean annual precipitation in Figure 2.2. Find the mean annual precipitation in inches at the centroid by interpolation.
6. Calculate the discharge with the equation for the desired recurrence interval from Table 3.4.

5.2 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 34,530 ft and the average slope of the main channel is 0.0032 ft/ft. Compute estimates of the 50-year discharge (Q_{50}) using the three-variable regression equation for Q_{50}.

Solution

1. The main channel length is 34,530 ft and the slope is 0.0032 ft/ft.

2. Compute the time of concentration with Equation 2.1.

$$\mathrm{t_c} = 0.0368\left(\frac{\mathrm{L}}{\sqrt{\mathrm{Sl}}}\right)^{0.66} = 0.0368\left(\frac{34530}{\sqrt{0.0032}}\right)^{0.66} = 242.3 \text{ min} = 4.04 \text{ hr}$$

3. Obtain the 50-year point-rainfall intensity for a duration of 4.04 hours by interpolation in KDOT's rainfall intensity table (McEnroe & Young, 2014) for Nemaha County.

$$\mathrm{Ip}_{50} = 1.29 + (1.23 - 1.29) \cdot \frac{4.04 - 4.00}{4.25 - 4.00} = 1.279 \text{ in./hr}$$

4. Compute the corresponding 50-year rainfall intensity over the 9.87-mi^2 watershed with Equations 2.2 and 2.3.

$$\mathrm{BV} = 0.355 \cdot \mathrm{D}^{-0.428} = 0.355 \cdot \mathrm{t}_c{}^{-0.428} = 0.355 \cdot (4.04)^{-0.428} = 0.195$$

$$\begin{aligned}\mathrm{Ia}_{ARI}(\mathrm{D}) &= \mathrm{Ip}_{ARI}(\mathrm{D}) \cdot [1 - \mathrm{BV} \cdot (1 - \mathrm{e}^{-0.015 \cdot \mathrm{A}})] \\ &= 1.279 \cdot [1 - 0.195 \cdot (1 - \mathrm{e}^{-0.015 \cdot 9.87})] = 1.244 \text{ in./hr}\end{aligned}$$

$\mathrm{Ia}_{50} = 1.244$ in./hr

5. Refer to Figure 2.2 to obtain the MAP for the watershed.

MAP = 34.9 in.

6. Compute Q_{50} with the three-variable regression equation from Table 3.4.

$$
\begin{aligned}
Q_{50} &= 9.77 \cdot MAP^{1.120} \cdot (Ia_{50} \cdot A)^{1.004} \\
&= 9.77 \cdot (34.9)^{1.120} \cdot (1.244 \cdot 9.87)^{1.004} \\
&= 6480 \text{ cfs} \qquad \text{(rounded to three significant figures)}
\end{aligned}
$$

Estimate has standard errors of +73%, -42%.

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Appendix

Table A.1: USGS Streamflow-Gaging Records in Data Set

Site Number	Site Name	County	Drainage Area (mi^2)	Years of Record
6813700	Tennessee Creek tributary near Seneca	Nemaha	0.90	33
6815700	Buttermilk Creek near Willis	Brown	3.70	52
6818200	Doniphan Creek at Doniphan	Doniphan	4.13	11
6844800	South Fork Sappa Creek tributary near Goodland	Sherman	21.12	33
6846200	Beaver Creek tributary near Ludell	Rawlins	10.68	33
6847600	Prairie Dog Creek tributary at Colby	Thomas	8.09	56
6848200	Prairie Dog Creek tributary near Norton	Norton	1.07	35
6856800	Moll Creek near Green	Clay	4.49	34
6858700	North Fork Smoky Hill River tributary near Winona	Logan	0.94	21
6863400	Big Creek tributary near Ogallah	Trego	4.90	52
6863700	Big Creek tributary near Hays	Ellis	6.06	56
6864300	Smoky Hill River tributary at Dorrance	Russell	5.51	56
6864700	Spring Creek near Kanopolis	Ellsworth	9.70	33
6866800	Saline River tributary at Collyer	Trego	3.54	33
6867800	Cedar Creek tributary near Bunker Hill	Russell	1.09	21
6868300	Coon Creek tributary near Luray	Osborne	6.54	56
6868700	North Branch Spillman Creek near Ash Grove	Lincoln	27.03	15
6868900	Bullfoot Creek tributary near Lincoln	Lincoln	2.89	33
6872600	Oak Creek at Bellaire	Smith	5.38	33
6873300	Ash Creek tributary near Stockton	Rooks	0.86	55
6873800	Kill Creek tributary near Bloomington	Osborne	1.43	21
6874500	East Limestone Creek near Ionia	Jewell	26.64	38
6876200	Middle Pipe Creek near Miltonvale	Cloud	9.71	21
6877200	West Turkey Creek near Elmo	Dickinson	26.18	21
6877400	Turkey Creek tributary near Elmo	Dickinson	2.49	21
6879700	Wildcat Creek at Riley	Riley	13.77	21
6884100	Mulberry Creek tributary near Haddam	Washington	1.55	32
6884300	Mill Creek tributary near Washington	Washington	2.92	55
6887200	Cedar Creek near Manhattan	Pottawatomie	14.93	56
6887600	Kansas River tributary near Wamego	Wabaunsee	0.82	35
6888600	Dry Creek near Maple Hill	Wabaunsee	15.88	22
6888900	Blacksmith Creek tributary near Valencia	Shawnee	0.76	33
6889100	Soldier Creek near Goff	Nemaha	2.05	23
6889120	Soldier Creek near Bancroft	Nemaha	10.58	24
6889140	Soldier Creek near Soldier	Nemaha	17.00	34

Table A.1: USGS Streamflow-Gaging Records in Data Set (Continued)

Site Number	Site Name	County	Drainage Area (mi^2)	Years of Record
6889550	Indian Creek near Topeka	Shawnee	9.81	43
6889600	South Branch Shunganunga Creek near Pauline	Shawnee	4.11	26
6890000	Little Delaware River near Horton	Brown	19.14	12
6890300	Spring Creek near Wetmore	Nemaha	20.86	21
6890560	Rock Creek 6 miles north of Meriden	Jefferson	1.92	14
6890600	Rock Creek near Meriden	Jefferson	22.09	14
6890700	Slough Creek tributary near Oskaloosa	Jefferson	0.85	21
6891050	Stone House Creek at Williamstown	Jefferson	13.22	26
6892940	Turkey Creek at Kansas City, KS	Wyandotte	22.22	14
6893350	Tomahawk Creek near Overland Park	Johnson	21.67	17
6912300	Dragoon Creek tributary near Lyndon	Osage	3.73	34
6913600	Rock Creek near Ottawa	Franklin	11.19	21
6914250	South Fork Pottawatomie Creek tributary near Garnett	Anderson	0.40	46
6914950	Big Bull near Edgerton, KS	Johnson	29.02	21
6914990	Little Bull Creek near Spring Hill	Johnson	8.00	21
6916700	Middle Creek near Kincaid	Anderson	2.16	34
6917100	Marmaton River tributary near Bronson	Allen	0.90	34
6917400	Marmaton River tributary near Fort Scott	Bourbon	2.83	56
7138800	Lion Creek tributary near Modoc	Scott	8.21	21
7139700	Arkansas River tributary near Dodge City	Ford	9.34	54
7140300	Whitewoman Creek near Bellefont	Hodgeman	18.39	33
7140600	Pawnee River tributary near Kalvesta	Finney	26.81	33
7141400	South Fork Walnut Creek tributary near Dighton	Lane	1.43	21
7141600	Long Branch Creek near Ness City	Ness	29.59	33
7141800	Otter Creek near Rush Center	Rush	17.41	33
7142100	Rattlesnake Creek tributary near Mullinville	Kiowa	10.00	33
7143100	Little Cheyenne Creek tributary near Clafin	Barton	1.53	56
7143200	Plum Creek near Holyrood	Ellsworth	19.13	21
7143500	Little Arkansas River near Geneseo	Rice	24.51	21
7144850	South Fork South Fork Ninnescah River near Pratt	Pratt	21.59	19
7144900	South Fork Ninnescah River tributary near Pratt	Pratt	1.59	33
7145300	Clear Creek near Garden Plain	Sedgwick	5.24	33
7145800	Antelope Creek tributary near Dalton	Sumner	0.41	34
7146700	West Branch Walnut River tributary near Degraff	Butler	10.18	21
7147020	Whitewater River tributary near Towanda	Butler	0.18	47
7147200	Dry Creek tributary near Augusta	Butler	0.89	21
7147990	Cedar Creek tributary near Cambridge	Cowley	2.52	52
7148700	Dog Creek near Deerhead	Barber	5.03	21

Table A.1: USGS Streamflow-Gaging Records in Data Set (Continued)

Site Number	Site Name	County	Drainage Area (mi^2)	Years of Record
7148800	Medicine Lodge River tributary near Medicine Lodge	Barber	2.15	21
7151600	Rush Creek near Harper	Harper	11.89	33
7156600	Cimarron River tributary near Moscow	Seward	19.68	33
7156700	Cimarron River tributary near Satanta	Seward	3.03	49
7157400	Crooked Creek tributary at Meade	Meade	8.46	33
7166200	Sandy Creek near Yates Center	Woodson	6.93	56
7166700	Burnt Creek at Reece	Greenwood	9.13	13
7169200	Salt Creek near Severy	Greenwood	7.65	21
7169700	Snake Creek near Howard	Elk	1.80	21
7170600	Cherry Creek near Cherryvale	Montgomery	15.13	21
7170800	Mud Creek near Mound Valley	Labette	4.42	34
7171700	Spring Branch near Cedar Vale	Chautauqua	3.10	38
7171800	Cedar Creek tributary near Hooser	Cowley	0.55	34
7171900	Grant Creek near Wauneta	Chautauqua	19.52	21
7180300	Spring Creek tributary near Florence	Marion	0.58	34
7182520	Rock Creek at Burlington	Coffey	8.23	21
7183800	Limestone Creek near Beulah	Crawford	13.13	33
7184600	Fly Creek near Faulkner	Cherokee	26.63	21

Table A.2: Flood Discharges from Frequency Analysis of Station Data

(Return period here defined as 1/AEP)

Site Number	Q2 (cfs)	Q5 (cfs)	Q10 (cfs)	Q25 (cfs)	Q50 (cfs)	Q100 (cfs)
6813700	201	497	793	1300	1785	2370
6815700	1210	2556	3737	5559	7153	8946
6818200	1073	2481	3831	6072	8164	10642
6844800	54	383	999	2649	4846	8201
6846200	200	725	1350	2525	3706	5166
6847600	178	464	740	1187	1590	2048
6848200	184	365	508	709	869	1037
6856800	348	820	1257	1951	2568	3270
6858700	247	505	711	1004	1240	1488
6863400	100	616	1468	3494	5929	9344
6863700	59	188	337	619	910	1279
6864300	184	575	1004	1767	2508	3402
6864700	390	1306	2353	4273	6177	8509
6866800	163	558	1026	1912	2816	3951
6867800	116	253	367	535	673	821
6868300	313	988	1747	3140	4530	6249
6868700	344	1087	1938	3533	5158	7207
6868900	95	226	347	542	717	916
6872600	93	267	459	816	1179	1640
6873300	27	128	278	615	1010	1561
6873800	209	581	961	1608	2214	2928
6874500	606	1313	1933	2886	3712	4636
6876200	535	1274	1990	3186	4305	5633
6877200	1192	2216	3015	4139	5048	6009
6877400	292	840	1424	2456	3459	4677
6879700	936	2009	2959	4433	5729	7192
6884100	164	415	671	1119	1555	2090
6884300	422	978	1499	2343	3112	4004
6887200	1401	4042	6902	12040	17116	23369
6887600	223	471	684	1007	1284	1590
6888600	1704	3285	4627	6666	8437	10429
6888900	349	775	1152	1730	2230	2787
6889100	428	988	1535	2461	3345	4412
6889120	1280	2407	3367	4836	6126	7588
6889140	1890	3398	4641	6500	8097	9883
6889550	1222	2080	2725	3612	4320	5063
6889600	911	1746	2438	3460	4327	5281
6890000	667	1016	1265	1597	1857	2125
6890300	1612	3687	5731	9231	12605	16720

Table A.2: Flood Discharges from Frequency Analysis of Station Data (Continued)

(Return period here defined as 1/AEP)

Site Number	Q2 (cfs)	Q5 (cfs)	Q10 (cfs)	Q25 (cfs)	Q50 (cfs)	Q100 (cfs)
6890560	411	852	1235	1818	2325	2891
6890600	2097	3221	4037	5144	6020	6938
6890700	172	485	821	1417	2003	2721
6891050	1708	3709	5498	8294	10767	13573
6892940	4807	8029	10539	14125	17093	20315
6893350	2952	5356	7295	10122	12494	15088
6912300	1136	3107	5149	8692	12090	16178
6913600	601	1303	1956	3019	3998	5149
6914250	148	295	415	590	735	891
6914950	3278	5096	6384	8084	9395	10739
6914990	1207	1991	2573	3372	4008	4676
6916700	673	1334	1870	2642	3277	3956
6917100	199	356	474	634	759	889
6917400	844	1359	1719	2184	2536	2888
7138800	90	182	253	351	426	504
7139700	121	534	1060	2068	3078	4306
7140300	182	708	1386	2754	4223	6139
7140600	257	740	1241	2096	2898	3842
7141400	55	108	147	200	240	280
7141600	63	440	1116	2834	5009	8183
7141800	396	949	1456	2250	2945	3724
7142100	380	1190	2033	3446	4734	6204
7143100	86	189	277	406	513	628
7143200	575	1200	1744	2578	3305	4120
7143500	956	1318	1543	1811	2000	2182
7144850	670	1568	2377	3626	4711	5916
7144900	331	712	1022	1459	1809	2174
7145300	598	1073	1421	1884	2239	2598
7145800	130	241	326	443	535	630
7146700	1319	2436	3316	4565	5585	6674
7147020	87	181	257	366	454	546
7147200	227	372	475	610	713	817
7147990	497	1606	2802	4869	6806	9068
7148700	272	938	1699	3076	4421	6044
7148800	134	507	948	1758	2551	3505
7151600	1197	2276	3108	4258	5168	6113
7156600	464	1394	2318	3800	5097	6531
7156700	106	450	874	1666	2443	3373
7157400	294	1287	2577	5106	7707	10947

Table A.2: Flood Discharges from Frequency Analysis of Station Data (Continued)

(Return period here defined as 1/AEP)

Site Number	Q2 (cfs)	Q5 (cfs)	Q10 (cfs)	Q25 (cfs)	Q50 (cfs)	Q100 (cfs)
7166200	1170	1991	2587	3379	3990	4612
7166700	1647	4109	6530	10583	14370	18847
7169200	2634	5245	7356	10379	12852	15486
7169700	469	1027	1504	2214	2811	3459
7170600	2460	4653	6437	9041	11221	13597
7170800	1281	2175	2847	3773	4512	5289
7171700	801	2160	3463	5536	7360	9397
7171800	147	330	485	710	893	1087
7171900	2452	6889	11364	18825	25679	33605
7180300	115	292	456	714	938	1187
7182520	1024	2375	3648	5720	7616	9825
7183800	3126	6533	9429	13758	17432	21463
7184600	4193	11023	17930	29706	40851	54133

Table A.3: Physical Characteristics of Gaged Watersheds

Site Number	Channel Length (ft)	Shape Factor	Channel Slope (ft/ft)	Time of Concen. (min)	Soil Perm. (in./hr)	Mean Annual Precipitation (in.)
6813700	10586	4.47	0.01185	72.12	0.458	34.6
6815700	19679	3.75	0.00449	149.70	0.602	36.2
6818200	20729	3.73	0.00795	128.22	1.164	37.6
6844800	69902	8.30	0.00254	416.76	1.291	18.9
6846200	38697	5.03	0.00641	207.84	1.289	20.9
6847600	36501	5.91	0.00343	245.82	1.291	20.4
6848200	11484	4.42	0.01009	80.28	1.300	23.4
6856800	27176	5.90	0.00399	192.60	0.732	32.0
6858700	9166	3.21	0.01282	63.90	1.294	19.4
6863400	41084	12.36	0.00354	262.98	1.300	23.3
6863700	46892	13.02	0.00336	292.02	1.219	25.1
6864300	26437	4.55	0.00490	176.64	1.306	27.3
6864700	47525	8.35	0.00370	285.48	1.314	28.7
6866800	20164	4.12	0.00598	138.30	1.300	22.1
6867800	9087	2.72	0.02832	48.96	1.280	26.9
6868300	27255	4.07	0.00833	151.32	1.240	26.8
6868700	85393	9.68	0.00287	456.78	1.136	27.7
6868900	27298	9.25	0.00580	170.64	1.300	28.6
6872600	33507	7.49	0.00449	212.52	1.300	26.7
6873300	10222	4.36	0.01011	74.28	1.300	24.7
6873800	15238	5.82	0.00789	104.94	1.275	26.3
6874500	94016	11.90	0.00237	519.00	1.257	27.5
6876200	50049	9.25	0.00402	287.46	1.000	30.0
6877200	77648	8.26	0.00202	481.98	0.489	33.2
6877400	22651	7.39	0.00595	149.64	0.442	33.1
6879700	56158	8.21	0.00222	377.40	0.625	33.0
6884100	11869	3.27	0.00914	84.78	1.213	30.8
6884300	17572	3.80	0.00803	114.66	0.987	31.8
6887200	46052	5.09	0.00740	222.42	0.736	34.1
6887600	9810	4.20	0.01808	59.70	0.613	35.5
6888600	46760	4.94	0.00391	277.38	0.657	36.6
6888900	10808	5.50	0.01130	74.28	0.563	37.4
6889100	17862	5.59	0.00498	135.66	0.471	35.4
6889120	35730	4.33	0.00340	243.18	0.468	35.6
6889140	52568	5.83	0.00270	338.70	0.464	35.7
6889550	41818	6.40	0.00417	252.12	0.584	37.7
6889600	24024	5.03	0.00520	162.66	0.553	37.9
6890000	60414	6.84	0.00227	392.88	0.512	36.2

Table A.3: Physical Characteristics of Gaged Watersheds (Continued)

Site Number	Channel Length (ft)	Shape Factor	Channel Slope (ft/ft)	Time of Concen. (min)	Soil Perm. (in./hr)	Mean Annual Precipitation (in.)
6890300	55551	5.31	0.00381	313.32	0.458	35.7
6890560	15792	4.66	0.00788	107.46	0.584	37.4
6890600	71301	8.26	0.00228	437.64	0.604	37.8
6890700	9456	3.78	0.00928	72.60	0.518	38.5
6891050	41775	4.73	0.00653	217.32	0.830	38.8
6892940	59532	5.72	0.00423	316.80	1.205	41.1
6893350	65129	7.02	0.00289	381.30	0.863	41.6
6912300	16220	2.53	0.00718	112.80	0.706	38.7
6913600	50107	8.05	0.00190	368.40	0.702	40.3
6914250	5349	2.58	0.02125	37.92	0.850	41.3
6914950	53212	3.50	0.00294	331.80	0.875	40.8
6914990	33708	5.09	0.00302	243.36	0.925	41.2
6916700	14736	3.61	0.00766	103.68	1.091	42.1
6917100	9984	3.99	0.00620	85.92	1.118	42.9
6917400	19457	4.81	0.00657	130.98	1.014	44.6
7138800	56311	13.85	0.00194	395.34	1.244	19.6
7139700	49442	9.39	0.00269	325.68	1.614	22.4
7140300	66760	8.69	0.00219	424.98	1.251	23.9
7140600	75092	7.54	0.00159	510.42	0.741	21.2
7141400	17435	7.63	0.00307	156.60	1.274	21.2
7141600	123156	18.39	0.00210	645.24	1.299	22.6
7141800	68941	9.79	0.00271	404.34	1.293	24.9
7142100	55023	10.86	0.00208	380.28	1.251	25.0
7143100	17091	6.85	0.00389	142.98	1.336	27.8
7143200	62594	7.35	0.00207	414.42	1.334	28.0
7143500	55920	4.58	0.00247	362.94	1.223	29.4
7144850	70272	8.20	0.00203	450.72	2.346	27.8
7144900	13966	4.40	0.00450	119.28	2.821	28.2
7145300	29003	5.76	0.00347	210.48	1.291	33.1
7145800	7772	5.24	0.00917	64.08	0.585	35.8
7146700	52573	9.74	0.00255	344.94	0.634	36.2
7147020	5407	5.76	0.01222	45.84	0.435	35.5
7147200	7476	2.25	0.00907	62.64	0.435	36.1
7147990	19346	5.33	0.01012	113.16	0.799	39.0
7148700	20840	3.10	0.01234	111.30	1.868	28.0
7148800	17672	5.21	0.00679	121.62	1.865	29.4
7151600	60113	10.90	0.00384	329.28	1.768	32.0
7156600	61047	6.79	0.00446	316.56	2.298	19.0

Table A.3: Physical Characteristics of Gaged Watersheds (Continued)

Site Number	Channel Length (ft)	Shape Factor	Channel Slope (ft/ft)	Time of Concen. (min)	Soil Perm. (in./hr)	Mean Annual Precipitation (in.)
7156700	25455	7.67	0.00621	159.30	3.443	19.4
7157400	51174	11.10	0.00601	255.36	1.068	21.5
7166200	29668	4.56	0.00420	200.52	0.781	40.9
7166700	34674	4.72	0.00683	189.36	0.697	38.3
7169200	24732	2.87	0.00637	155.04	0.637	39.8
7169700	11933	2.84	0.00937	84.36	0.551	40.0
7170600	39019	3.61	0.00322	262.50	0.893	42.8
7170800	19980	3.24	0.00563	140.28	1.173	43.3
7171700	18079	3.78	0.00861	114.12	0.700	40.4
7171800	8987	5.30	0.02799	48.78	0.700	39.8
7171900	54806	5.52	0.00398	306.06	0.781	40.8
7180300	8110	4.05	0.00971	64.62	0.611	35.3
7182520	34684	5.24	0.00246	265.38	0.687	40.0
7183800	34119	3.18	0.00298	246.36	0.771	45.2
7184600	52964	3.78	0.00171	395.22	1.091	45.2

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