Report No. K-TRAN: KU-02-4
FINAL REPORT

STORM DURATION AND ANTECEDENT MOISTURE CONDITIONS FOR FLOOD DISCHARGE ESTIMATION

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NOVEMBER 2003

K-TRAN

A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:
KANSAS DEPARTMENT OF TRANSPORTATION
KANSAS STATE UNIVERSITY
THE UNIVERSITY OF KANSAS

1 Report No.
K-TRAN: KU-02-4

2 Government Accession No.

3 Recipient Catalog No.

4 Title and Subtitle
STORM DURATION AND ANTECEDENT MOISTURE CONDITIONS FOR FLOOD DISCHARGE ESTIMATION

5 Report Date
November 2003

6 Performing Organization Code

7 Author(s)
Bruce M. McEnroe and Pablo Gonzalez, University of Kansas

8 Performing Organization Report No.

9 Performing Organization Name and Address
The University of Kansas
1530 West 15th Street
Lawrence, Kansas 66045

10 Work Unit No. (TRAIS)

11 Contract or Grant No.
C1273

12 Sponsoring Agency Name and Address
Kansas Department of Transportation
Bureau of Materials and Research, Research Unit
2300 Southwest Van Buren Street
Topeka, Kansas 66611-1195

13 Type of Report and Period Covered
Final Report
July 2001 – March 2003

14 Sponsoring Agency Code
RE-0287-01

15 Supplementary Notes
For more information write to address in block 9.

16 Abstract

Design flows estimated by flood hydrograph simulation can be reasonably accurate or greatly in error, depending upon the modeling procedures and inputs selected. The objectives of this research project were (1) to determine which combinations of modeling procedures and inputs yield the best discharge estimates under various conditions and (2) to develop specific guidelines for flood hydrograph simulation for possible inclusion in the KDOT Design Manual.

Many different combinations of modeling procedures and inputs were tested in flood simulations for 66 gaged watersheds in Kansas. The test watersheds were all primarily rural with unregulated streams, drainage areas under 50 km^2 and gaging records of 20 years or longer. The simulations were performed with the HEC-1 computer program of the U. S. Army Corps of Engineers. The key inputs were the duration of the hypothetical frequency-based storm and the antecedent moisture condition (AMC) in the NRCS loss model. Floods with six different recurrence intervals (2, 5, 10, 25, 50 and 100 years) were simulated using four different storm durations (3, 6, 12 and 24 hours), five different antecedent moisture conditions (AMC 2, 2¼, 2½, 2¾ and 3) and the two different unit-hydrograph models (NRCS and Snyder). The results for the watersheds in eastern and western Kansas were analyzed separately. We computed the bias and standard error of the simulated flows, relative to the gage-based estimates, for each combination of recurrence interval, storm duration, AMC and unit-hydrograph model in each region. From these results, we identified combinations of storm durations and AMCs that yield unbiased discharge estimates for each set of conditions. Longer storm durations and/or higher AMCs are needed for higher recurrence intervals. The storm durations are shorter and the AMCs are lower in the western region than in the eastern region.

Flood hydrograph simulation with the recommended inputs is approximately as accurate as the USGS regression equations in eastern Kansas and more accurate than the USGS regression equations in western Kansas. The standard errors of the simulated flows are larger in western Kansas than in eastern Kansas.

We recommend simplified guidelines for flood hydrograph simulation for inclusion in the KDOT Design Manual, Volume I, Part C. These guidelines specify the NRCS UH model and a single combination of storm duration and AMC for each recurrence interval and region.

16 Key Words
Computer Program, Design, Discharge, Flood, Gage, Hydrograph, Regression Equation, Storm Duration, and Watershed

17 Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

18 Security Classification (of this report)
Unclassified

19 Security Classification (of this page)
Unclassified

20 No. of pages
50

21 Price

Form DOT F 1700.7 (8-72)

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Final Report

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A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

UNIVERSITY OF KANSAS
LAWRENCE, KANSAS

November 2003

PREFACE

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

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ABSTRACT

Design flows estimated by flood hydrograph simulation can be reasonably accurate or greatly in error, depending upon the modeling procedures and inputs selected. The objectives of this research project were (1) to determine which combinations of modeling procedures and inputs yield the best discharge estimates under various conditions and (2) to develop specific guidelines for flood hydrograph simulation for possible inclusion in the KDOT Design Manual.

Many different combinations of modeling procedures and inputs were tested in flood simulations for 66 gaged watersheds in Kansas. The test watersheds were primarily rural with unregulated streams, drainage areas under 50 km^2 and gaging records of 20 years or longer. The simulations were performed with the HEC-1 computer program of the U. S. Army Corps of Engineers. The key inputs were the duration of the hypothetical frequency-based storm and the antecedent moisture condition (AMC) in the NRCS loss model. Floods with six different recurrence intervals (2, 5, 10, 25, 50 and 100 years) were simulated using four different storm durations (3, 6, 12 and 24 hours), five different antecedent moisture conditions (AMC 2, 2¼, 2½, 2¾ and 3) and the two different unit-hydrograph models (NRCS and Snyder). The results for the watersheds in eastern and western Kansas were analyzed separately. We computed the bias and standard error of the simulated flows, relative to the gage-based estimates, for each combination of recurrence interval, storm duration, AMC and unit-hydrograph model in each region. From these results, we identified combinations of storm durations and AMCs that yield unbiased discharge estimates for each set of conditions. Longer storm durations and/or higher AMCs are needed for higher recurrence intervals. The storm durations are shorter and the AMCs are lower in the western region than in the eastern region.

Flood hydrograph simulation with the recommended inputs is approximately as accurate as the USGS regression equations in eastern Kansas and more accurate than the USGS regression equations in western Kansas. The standard errors of the simulated flows are larger in western Kansas than in eastern Kansas.

We recommend simplified guidelines for flood hydrograph simulation for inclusion in the KDOT Design Manual, Volume I, Part C. These guidelines specify the NRCS UH model and a single combination of storm duration and AMC for each recurrence interval and region.

ACKNOWLEDGMENTS

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

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1.1 Design Flows for Drainage Structures

Drainage structures such as culverts and bridges are designed for floods with specified recurrence intervals. Design flows for drainage structures are generally estimated by one of three methods: the rational method, the USGS regression equations or flood hydrograph simulation. The rational method is not recommended for watersheds larger than a few hundred acres, the USGS regression equations are not applicable to urban watersheds, and neither method is applicable to regulated streams. The method of flood hydrograph simulation is not subject to these limitations. In many situations, flood hydrograph simulation (using a computer program such as HEC-1 or HEC-HMS of the Army Corps of Engineers) is the best method available for estimation of design flows. The major problem with this method is that the computed peak discharge depends strongly on the assumed storm duration, the assumed antecedent moisture condition and other factors.

1.2 Objectives

The objectives of this research project were (1) to determine which combinations of storm duration and antecedent moisture condition yield the best estimates of flood discharges under various conditions and (2) to develop specific guidelines for design-flow estimation by flood hydrograph simulation.

Chapter 2

Design Flows by Flood Hydrograph Simulation

2.1 Overview of Flood Hydrograph Simulation

In its simplest form, a flood-hydrograph simulation model has two components: a loss model and a hydrograph model. Figure 2.1 shows the general structure. The event-specific inputs are a rainfall hyetograph (a record of incremental rainfall versus time) and an antecedent soil-moisture condition. Other inputs, which are not event-specific, describe relevant characteristics of the watershed. The loss model accounts for infiltration, interception and depression storage. The rainfall that is not lost to infiltration, interception or depression storage is termed excess rainfall. The output from the loss model is a hyetograph of excess rainfall. The hydrograph model transforms the excess rainfall hyetograph into a streamflow hydrograph at the watershed outlet, accounting for the time of travel and storage effects.

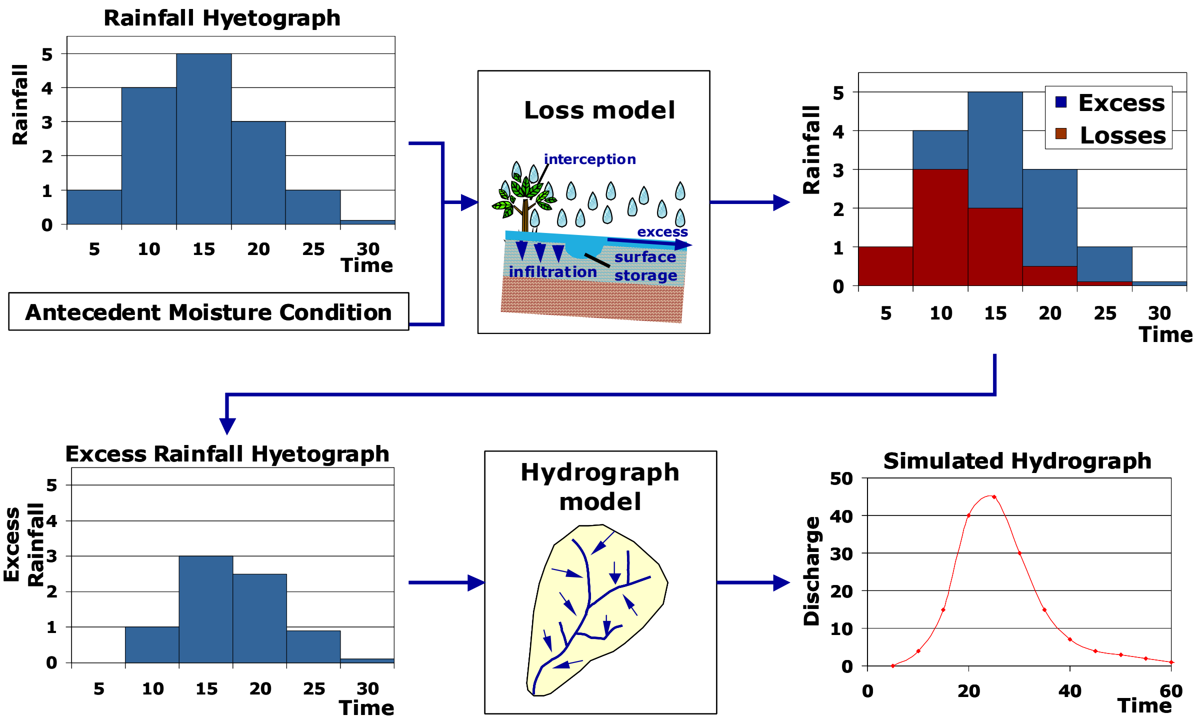

FIGURE 2.1: Diagram Describing the General Flood Hydrograph Simulation Procedure

2.2 Loss Model

The loss model must account for the effects of surface conditions, soil properties and antecedent moisture conditions. The HEC-1 and HEC-HMS computer programs offer several different loss models. The most widely used loss model is the curve-number model of the Natural Resources Conservation Service (NRCS). The principal input to the NRCS loss model is a runoff curve number (CN), which depends on surface conditions, soil characteristics and antecedent moisture conditions.

In the NRCS curve-number model, soils are classified into four hydrologic soil groups, identified as A, B, C and D. Group A soils have high infiltration rates, even when thoroughly wetted, and low runoff potential. These soils are generally deep, very well drained sands or gravels. Group B soils have moderate infiltration rates. They are fairly deep and well drained soils with moderately fine to moderately coarse textures. Group C soils have low infiltration rates. This group includes soils with moderately fine to fine textures and soils with a layer that impedes downward movement of water. Group D soils have very low infiltration rates. This group includes clay soils, soils with a clay layer near the surface, shallow soils over rock, and soils with permanent high water tables.

The antecedent moisture condition (AMC) is indicated by an index with a minimum value of one and a maximum value of three. AMC 1 represents a condition that is unusually dry but not necessarily the driest possible condition. AMC 3 represents a condition that is unusually wet but not necessarily the wettest possible condition. AMC 2 represents an intermediate moisture condition.

Curve numbers for AMC 2 can be estimated from the surface type and condition and the hydrologic soil group using tables developed by the NRCS (NRCS, 1972), which appear in many standard references. The corresponding curve numbers for AMC 1 and AMC 3 can be computed with Equations 1 and 2 (Chow et. al., 1988), and curve numbers for fractional AMC values (e.g., AMC 2½) can be obtained by linear interpolation.

$$\mathrm{CN}_1 = \frac{4.2\ \mathrm{CN}_2}{10 - 0.058\ \mathrm{CN}_2} \qquad (1)$$

$$\mathrm{CN}_3 = \frac{23\ \mathrm{CN}_2}{10 + 0.13\ \mathrm{CN}_2} \qquad (2)$$

2.3 Hydrograph Model

The hydrograph model typically uses a synthetic unit hydrograph to transform the excess rainfall into streamflow at the watershed outlet. In HEC-1 and HEC-HMS, synthetic unit hydrographs can be developed by several different methods. The two most widely used methods are those of Snyder and the NRCS. The Snyder synthetic unit-hydrograph (UH) model in HEC-1 and HEC-

HMS requires three inputs: drainage area, lag time and a peaking coefficient. The Snyder synthetic unit hydrograph has a variable shape, which is determined by the value of the peaking coefficient, C_p. McEnroe and Zhao (1999) recommend $C_p = 0.62$ as a typical value for rural watersheds in Kansas with drainage areas under 50 km^2. The NRCS synthetic UH model, which has a fixed shape, requires two inputs: drainage area and lag time.

Lag time is a measure of how quickly runoff reaches the watershed outlet. The lag time of a unit hydrograph is defined as the time from the centroid of the excess rainfall to the peak on the hydrograph. Lag time can be estimated from physical characteristics of the watershed. Lag times of rural watersheds in Kansas with drainage areas under 50 km^2 can be estimated from the length and average slope of the main channel using a regression equation developed by McEnroe and Zhao (1999). This equation is

$$T_{lag} = 0.077 \cdot \left(\frac{L}{\sqrt{S}} \right)^{0.66} \tag{3}$$

in which T_{lag} is the lag time in hours, L is the total length of the main channel (extended to the drainage divide) in km, and S is the average slope of the main channel in m/m. The average slope of the main channel is defined as the elevation difference between two points, located 10% and 85% of the channel length from the outlet, divided by the length of channel between the two points (0.75 L). Equation 3 is a corrected version of the equation published in KDOT Report No. K-TRAN: KU-98-1, as explained in the errata sheet dated October 2001. Other regression equations developed for KDOT provide estimates of lag times for urban and developing watersheds in Kansas (McEnroe and Zhao, 2001).

2.4 Precipitation and Antecedent Moisture Conditions

When design flows are estimated by flood hydrograph simulation, the normal assumption is that the peak flow has the same recurrence interval as the rainfall input (the design storm). If the objective is to estimate the 100-year discharge, the design storm should have a combination of duration and depth with a 100-year recurrence interval. The design-storm duration is usually specified or selected arbitrarily. The corresponding rainfall depth for the desired recurrence interval is obtained from a rainfall depth-duration-frequency table for the subject area or the nationwide rainfall frequency maps of the National Weather Service. The problem with this approach is that the simulated peak discharge is strongly dependent on the selected storm duration, the temporal distribution of the rainfall, and the assumed antecedent moisture condition. The true recurrence interval of the peak discharge could be much higher or much lower than the recurrence interval of the rainfall input, depending on these factors.

Design rainfall can be distributed in a variety of temporal patterns. One widely accepted method for distributing storm rainfall is the alternating block method (Chow et. al., 1988). The frequency-based hypothetical storms in HEC-1 and HEC-HMS are developed by this method. This type of design storm has a nearly symmetrical temporal pattern with a single peak period that starts at the midpoint of the storm duration. The temporal distribution is such that the heaviest rainfall of any duration within the storm has the same recurrence interval as the total storm rainfall. The NRCS 24-hour storm distributions (Types I, II and III) are regionalized alternating-block distributions.

2.5 Proposed Standard Procedures

Design flows estimated by flood hydrograph simulation can be reasonably accurate or greatly in error, depending upon the models and inputs selected. Multiple combinations of inputs will yield flow estimates that are approximately correct. However, most combinations of inputs will produce poor results. Our objective is to develop a set of standard procedures for flood hydrograph simulation that will yield reasonably accurate estimates of design flows over a wide range of conditions.

Our proposed standard procedures for flood hydrograph simulation are as follows:

Software	HEC-1 or HEC-HMS
Loss model	NRCS curve-number model
Hydrograph model	NRCS unit hydrograph model, or Snyder unit hydrograph model with peaking coefficient of 0.62
Lag times	Regression equations for lag times of rural watersheds (McEnroe and Zhao, 1999) and urban and developing watersheds (McEnroe and Zhao, 2001)
Design storm	HEC hypothetical frequency-based storm

Chapter 3

Test of Flood Simulation Procedures

3.1 Overview of the Test

Flood hydrograph simulations were performed for 66 gaged watersheds in Kansas using the proposed standard procedures. Floods with six different recurrence intervals (2, 5, 10, 25, 50 and 100 years) were simulated using four different storm durations (3, 6, 12 and 24 hours), five different antecedent moisture conditions (AMC 2, 2¼, 2½, 2¾ and 3) and the two different unit-hydrograph models, for a total of 240 simulations per watershed. These simulations where performed using HEC-1 Version 4.1 (1998). The results for the watersheds in eastern and western Kansas were analyzed separately. We computed the bias and standard error of the simulated flows, relative to the gage-based estimates, for each combination of recurrence interval, storm duration, AMC and unit-hydrograph model in each region. From these results, we identified combinations of storm durations and AMCs that yield unbiased discharge estimates for each set of conditions.

3.2 Selection of the Test Watersheds

Our test focused on gaged rural watersheds with unregulated streams, drainage areas under 50 km2 and gaging records of 20 years or longer. The USGS streamflow database for Kansas includes 76 gaged watersheds that meet these criteria. We selected 66 of these watersheds for this test. The other ten watersheds were excluded due to large differences between the total drainage area and the contributing drainage area reported by the USGS. Most of the excluded watersheds were located in western Kansas. Table 3.1 lists the selected watersheds, and Figure 3.2 shows their locations.

TABLE 3.1: Selected USGS Streamflow-Gaging Stations

No.	Station ID	Station Name	County	Drainage Area (km^2)	Years of record
1	6813700	Tennessee Creek tributary near Seneca, Kansas	Nemaha	2.32	33
2	6815700	Buttermilk Creek near Willis, Kansas	Brown	9.57	40
3	6818260	White Clay Creek at Atchison, Kansas	Atchison	33.40	25
4	6846200	Beaver Creek tributary near Ludell, Kansas	Rawlins	27.32	33
5	6847600	Prairie Dog Creek tributary at Colby, Kansas	Thomas	20.28	41
6	6848200	Prairie Dog Creek tributary near Norton, Kansas	Norton	2.75	35
7	6856800	Moll Creek near Green, Kansas	Clay	10.32	34
8	6863400	Big Creek tributary near Ogallah, Kansas	Trego	12.45	41
9	6863700	Big Creek tributary near Hays, Kansas	Ellis	15.79	39
10	6864300	Smoky Hill River tributary at Dorrance, Kansas	Russell	14.16	41
11	6864700	Spring Creek near Kanopolis, Kansas	Ellsworth	24.84	33
12	6866800	Saline River tributary at Collyer, Kansas	Trego	8.85	33
13	6867800	Cedar Creek tributary near Bunker Hill, Kansas	Russell	2.79	21
14	6868300	Coon Creek tributary near Luray, Kansas	Osborne	16.76	41
15	6868900	Bullfoot Creek tributary near Lincoln, Kansas	Lincoln	7.52	31
16	6872600	Oak Creek at Bellaire, Kansas	Smith	13.92	33
17	6873300	Ash Creek tributary near Stockton, Kansas	Rooks	2.27	39
18	6873800	Kill Creek tributary near Bloomington, Kansas	Osborne	3.72	21
19	6876200	Middle Pipe Creek near Miltonvale, Kansas	Cloud	25.49	21
20	6877400	Turkey Creek tributary near Elmo, Kansas	Dickinson	6.43	21
21	6879700	Wildcat Creek at Riley, Kansas	Riley	35.06	21
22	6884100	Mulberry Creek tributary near Haddam, Kansas	Washington	4.18	32
23	6884300	Mill Creek tributary near Washington, Kansas	Washington	7.50	41
24	6887200	Cedar Creek near Manhattan, Kansas	Pottawatomie	36.27	32
25	6888600	Dry Creek near Maple Hill, Kansas	Wabaunsee	40.70	21
26	6889100	Soldier Creek near Goff, Kansas	Nemaha	5.36	23
27	6889120	Soldier Creek near Bancroft, Kansas	Nemaha	27.29	24
28	6889140	Soldier Creek near Soldier, Kansas	Nemaha	43.59	33
29	6889600	South Branch Shunganunga Creek near Pauline, Kansas	Shawnee	9.95	21
30	6890700	Slough Creek tributary near Oskaloosa, Kansas	Jefferson	2.18	21
31	6891050	Stone House Creek at Williamstown, Kansas	Jefferson	33.81	26
32	6912300	Dragoon Creek tributary near Lyndon, Kansas	Osage	9.44	34
33	6913600	Rock Creek near Ottawa, Kansas	Franklin	25.90	21
34	6914250	South Fork Pottawatomie Creek tributary near Garnett,	Anderson	0.95	34
35	6916700	Middle Creek near Kincaid, Kansas	Anderson	5.38	34
36	6917100	Marmaton River tributary near Bronson, Kansas	Allen	2.30	34
37	6917400	Marmaton River tributary near Fort Scott, Kansas	Bourbon	7.28	41
38	7139700	Arkansas River tributary near Dodge City, Kansas	Ford	24.24	39
39	7141400	South Fork Walnut Creek tributary near Dighton, Kansas	Lane	2.24	21
40	7141800	Otter Creek near Rush Center, Kansas	Rush	44.54	33
41	7142100	Rattlesnake Creek tributary near Mullinville, Kansas	Kiowa	25.86	33
42	7143100	Little Cheyenne Creek tributary near Claflin, Kansas	Barton	3.81	41
43	7143200	Plum Creek near Holyrood, Kansas	Ellsworth	49.07	20
44	7144900	South Fork Ninnescah River tributary near Pratt, Kansas	Pratt	3.79	32
45	7145300	Clear Creek near Garden Plain, Kansas	Sedgwick	13.11	33
46	7145800	Antelope Creek tributary near Dalton, Kansas	Sumner	1.03	33
47	7146700	West Branch Walnut River tributary near Degraff, Kansas	Butler	26.45	21

TABLE 3.1: Selected USGS Streamflow-Gaging Stations (continued)

No.	Station ID	Station Name	County	Drainage Area (km^2)	Years of record
48	7147020	Whitewater River tributary near Towanda, Kansas	Butler	0.45	34
49	7147200	Dry Creek tributary near Augusta, Kansas	Butler	2.28	21
50	7147990	Cedar Creek tributary near Cambridge, Kansas	Cowley	6.48	35
51	7148700	Dog Creek near Deerhead, Kansas	Barber	12.99	21
52	7148800	Medicine Lodge River tributary near Medicine Lodge, KS	Barber	5.53	21
53	7151600	Rush Creek near Harper, Kansas	Harper	30.33	33
54	7156700	Cimarron River tributary near Satanta, Kansas	Seward	10.43	38
55	7157400	Crooked Creek tributary at Meade, Kansas	Meade	17.42	33
56	7166200	Sandy Creek near Yates Center, Kansas	Woodson	17.64	41
57	7169200	Salt Creek near Severy, Kansas	Greenwood	19.48	21
58	7169700	Snake Creek near Howard, Kansas	Elk	4.67	21
59	7170600	Cherry Creek near Cherryvale, Kansas	Labette	38.82	21
60	7170800	Mud Creek near Mound Valley, Kansas	Labette	11.11	34
61	7171700	Spring Branch near Cedar Vale, Kansas	Chautauqua	7.99	38
62	7171800	Cedar Creek tributary near Hooser, Kansas	Cowley	1.39	34
63	7171900	Grant Creek near Wauneta, Kansas	Chautauqua	49.89	21
64	7180300	Spring Creek tributary near Florence, Kansas	Marion	1.50	34
65	7182520	Rock Creek at Burlington, Kansas	Coffey	21.42	21
66	7183800	Limestone Creek near Beulah, Kansas	Crawford	33.97	33

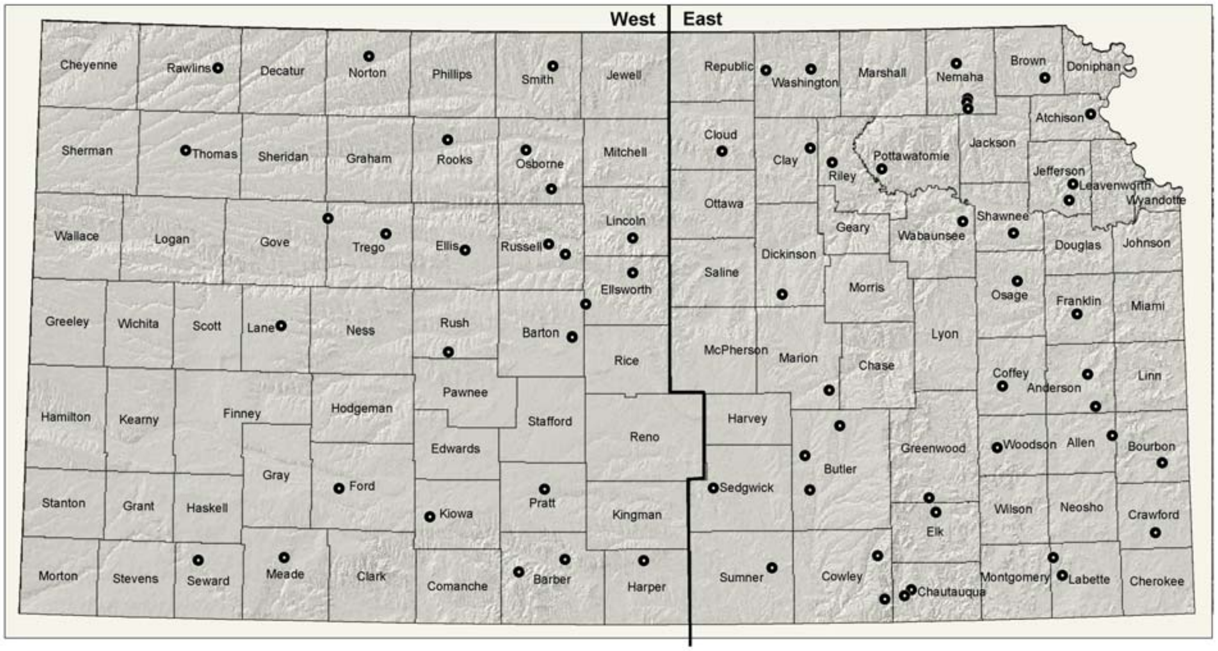

FIGURE 3.1: Location of Selected Watersheds

3.3 Discharge Estimates from Frequency Analysis of Streamflow Records

The gage-based discharge estimates were obtained from USGS Water-Resources Investigations Report 00-4079 (Rasmussen and Perry, 2000). WRI Report 00-4079 provides estimates of discharges for recurrence intervals from 2 years to 200 years (Q2…Q200) at gaging stations on unregulated streams in Kansas. These estimates were developed by the standard flood-frequency analysis procedure used by federal agencies (Interagency Advisory Committee on Water Data, 1981), except that generalized skewness coefficient was obtained from a regional regression equation for Kansas rather than the nationwide map. Table 3.2 lists the gaged-based discharge estimates for the selected watersheds.

TABLE 3.2: Discharge Estimates from Frequency Analysis of Streamflow Records

No.	Station ID	Q2 (m^3/s)	Q5 (m^3/s)	Q10 (m^3/s)	Q25 (m^3/s)	Q50 (m^3/s)	Q100 (m^3/s)
1	6813700	5.7	14.1	22.5	36.8	50.7	67.7
2	6815700	43.0	78.2	106.2	146.1	179.0	214.6
3	6818260	31.1	61.7	88.3	130.5	168.5	212.1
4	6846200	8.4	18.8	27.6	40.5	51.0	62.0
5	6847600	6.1	16.1	25.4	39.9	52.7	66.5
6	6848200	5.2	10.4	14.4	19.9	24.2	28.6
7	6856800	10.5	22.9	33.7	49.6	63.1	77.9
8	6863400	6.0	20.0	37.1	71.1	107.3	154.9
9	6863700	1.8	5.9	10.8	20.3	30.3	43.3
10	6864300	6.9	17.9	28.6	47.0	63.7	83.8
11	6864700	13.1	33.1	53.0	85.0	114.4	148.7
12	6866800	4.6	16.0	29.7	56.1	83.0	116.9
13	6867800	3.7	6.3	8.3	11.0	13.1	15.3
14	6868300	10.1	30.3	51.8	89.8	126.6	171.0
15	6868900	2.9	6.8	10.3	15.7	20.6	26.1
16	6872600	2.6	7.7	13.6	24.8	36.5	51.3
17	6873300	1.0	4.2	8.6	18.0	28.9	43.6
18	6873800	5.9	16.6	27.5	46.2	63.4	83.8
19	6876200	15.1	36.0	56.6	91.2	124.0	163.1
20	6877400	8.3	23.8	40.5	69.7	98.3	133.1
21	6879700	26.5	57.2	84.4	126.0	162.5	203.6
22	6884100	4.7	11.7	18.9	31.7	44.2	59.7
23	6884300	14.8	30.9	45.3	68.0	88.3	111.6
24	6887200	43.3	100.8	154.9	242.4	322.8	413.4
25	6888600	47.3	87.2	121.2	173.0	218.9	270.7
26	6889100	11.4	24.9	37.9	60.0	81.3	106.8
27	6889120	34.5	62.3	85.8	121.2	152.3	188.0
28	6889140	52.4	95.1	131.4	186.3	234.2	288.8
29	6889600	21.5	41.1	57.8	83.5	105.9	131.4
30	6890700	4.9	13.8	23.1	39.6	55.5	75.0
31	6891050	48.7	105.3	154.9	231.1	297.3	371.0
32	6912300	34.5	83.3	130.5	210.4	286.0	373.8
33	6913600	16.9	36.8	55.5	86.6	115.8	150.4
34	6914250	5.2	8.8	11.5	15.1	18.1	21.2
35	6916700	19.2	37.9	52.7	73.9	90.9	109.3
36	6917100	5.8	9.9	12.9	16.9	20.0	23.2
37	6917400	26.1	40.5	50.1	62.0	70.8	79.3
38	7139700	6.5	13.8	19.9	28.9	36.0	43.9
39	7141400	1.6	3.0	4.1	5.5	6.5	7.6

TABLE 3.2: Discharge Estimates from Frequency Analysis of Streamflow Records (continued)

No.	Station ID	Q2 (m^3/s)	Q5 (m^3/s)	Q10 (m^3/s)	Q25 (m^3/s)	Q50 (m^3/s)	Q100 (m^3/s)
40	7141800	11.2	27.0	41.6	64.6	84.7	107.3
41	7142100	11.8	30.9	49.0	77.9	103.4	132.2
42	7143100	3.0	5.0	6.4	8.4	10.0	11.6
43	7143200	18.6	34.8	47.9	67.1	83.5	101.4
44	7144900	10.6	19.3	25.9	35.1	42.5	49.8
45	7145300	17.3	30.0	39.1	51.0	60.0	68.8
46	7145800	3.8	6.9	9.3	12.5	15.1	17.8
47	7146700	37.1	69.1	94.9	131.4	161.7	194.0
48	7147020	2.4	4.9	7.0	10.0	12.5	15.1
49	7147200	6.4	10.6	13.5	17.5	20.6	23.8
50	7147990	16.3	47.0	77.6	128.3	174.1	226.5
51	7148700	7.7	26.6	48.4	88.1	127.1	174.7
52	7148800	3.8	14.4	26.7	49.3	71.1	97.1
53	7151600	33.7	64.8	88.9	122.0	148.7	176.1
54	7156700	5.7	16.3	26.4	41.9	55.2	69.4
55	7157400	8.3	36.8	74.2	147.8	223.7	317.1
56	7166200	35.1	56.4	71.6	91.2	105.9	120.9
57	7169200	83.5	144.7	189.7	250.0	297.3	345.5
58	7169700	14.1	27.4	38.5	54.4	67.7	81.8
59	7170600	71.6	129.7	176.4	244.7	303.0	365.3
60	7170800	36.0	61.7	81.3	108.7	131.1	154.6
61	7171700	23.1	60.9	96.0	150.4	197.1	247.8
62	7171800	4.2	9.4	13.7	20.0	25.0	30.3
63	7171900	89.5	156.0	204.7	269.9	320.0	371.0
64	7180300	3.3	8.2	12.7	19.7	25.5	32.0
65	7182520	28.9	67.1	103.6	163.1	217.8	282.0
66	7183800	88.9	185.2	266.2	385.1	487.0	597.5

3.4 GIS Data and Procedures

The development of the simulation models for the selected watersheds and the regional analysis of the test results required extensive processing of geospatial data. We performed the geospatial analyses with the ArcInfo and ArcView GIS software of ESRI. Geospatial data were transformed (if necessary) to the Lambert Conformal Conic projection and imported into ArcInfo as coverages or grids.

An ArcView shapefile of the gage locations for the selected watersheds was created from a listing of latitude-longitude coordinates for USGS streamflow gages in Kansas (Rasmussen and Perry, 2000). The gage-based discharge estimates in Table 2 and other relevant data were added to the shapefile's attribute database. A shapefile of watershed boundaries was created in ArcView using scanned USGS 24K topographic maps displayed as a background images. The Data Access Support Center (DASC) of the State of Kansas provided the scanned topographic maps (Digital Raster Graphics images).

The GIS database developed for this study includes the following thematic maps:

- Location of the discharge gages
- Watershed boundaries
- Soils
- Land Cover
- Rainfall (depth-duration-frequency)
- Annual lake evaporation

3.5 Watershed Characteristics for Flood Simulations

3.5.1 Drainage Areas and Lag Times

The drainage areas used in the simulations were calculated from the watershed boundaries shapefile using ArcView. Lag times of the selected watersheds were computed with Equation 3. The required channel lengths were obtained by digitally measuring them from the scanned USGS 24K topographic maps using ArcView. The required channel slopes were computed using the measured channel lengths and elevations obtained from the scanned 24K topographic maps.

3.5.2 Soils

Soil types were determined from the Detailed Soils 24K digital data set of the NRCS. The Soil Survey Geographic (SSURGO) dataset, the certified version of the Digital Soils 24K data set, was used where available. Our specific interest was the Hydrologic Soil Group attribute. 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 Data Access and Support Center (DASC) of the state of Kansas.

Because the soils map created for this study is a combination of two equivalent but slightly different data sets, some pre-processing was required. The Detailed Soils 24K map is tiled by the 1:24,000 USGS quadrangles while the SSURGO data set is aggregated at the county level. Individual tiles and counties are also located in two different UTM projection zones, 14 and 15. First, the individual tiles and counties were merged into four different maps: 24KUTM14, 24K-UTM15, SSURGO-UTM14 and SSURGO-UTM15. These maps were reprojected from UTM to Lambert Conformal Conic (LCC), reclassified according to Hydrologic Soil Group (hydro-group field), and clipped with the watershed boundaries coverage. The two 24K maps and the two SSURGO maps were merged to produce two new maps. Overlapping areas were eliminated by using ArcInfo's UPDATE command to "update" the 24K map with the SSURGO map. The resulting final soil map is a single coverage that contains the Hydrologic Soil Group classifications within the test watersheds.

Figure 3.2 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. In the eastern Kansas, soil groups C and D predominate with some occurrences of soil group B and a few occurrences of soil group A. In western Kansas, soil group B predominates with some occurrences of the other soil groups. Soil Group A occurs mainly in the Arkansas River lowlands.

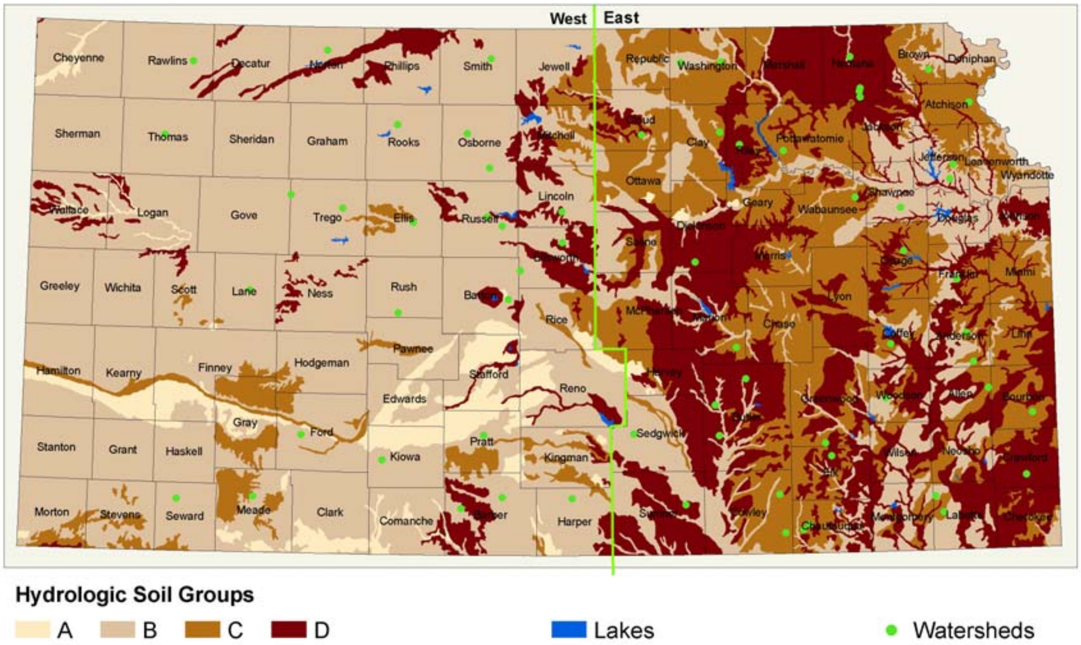

FIGURE 3.2: Hydrologic Soil Groups Map

3.5.3 Land Cover Data

Land cover data were obtained from the National Land Cover Data 1992 (NLCD 92) digital data set of the USGS. This data set depicts 21 land-cover classes. The USGS developed this data set from early to mid-1990s Landsat Thematic Mapper satellite data and a variety of supporting information. Figure 3.3 shows the land-cover data for Kansas aggregated into eight general classes. The predominant general land-cover classes in Kansas are Herbaceous Planted/Cultivated and Herbaceous Upland. To obtain the land cover data for the test watersheds, the land cover map with 21 classes was clipped with the watershed boundaries coverage.

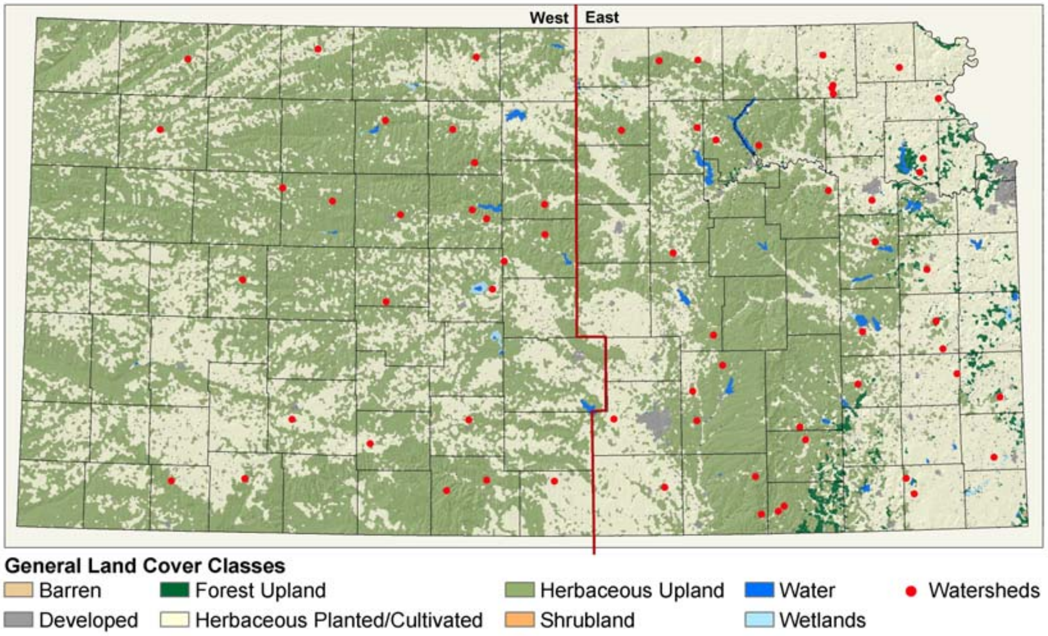

FIGURE 3.3: General Land Cover Map

3.5.4 Runoff Curve Numbers

The runoff curve number depends on three factors: hydrologic soil group, land use and antecedent moisture condition. Table 3.3 shows CN^2 (the curve number for AMC 2) for all possible combinations of the four hydrologic soil groups and the land uses in the selected watersheds. Table 3.3 was developed by matching the 19 land-cover classes of the USGS map to equivalent or similar land-cover classes in NRCS's National Engineering Handbook (NRCS, 1972). A combined soil-land cover map was created by overlaying the final soils map on the final land-cover map using ArcInfo's UNION command. A runoff curve number for AMC 2 was assigned to each combination of soil group and land-cover class according to Table 3.3. Equivalent curve numbers for AMC 3 were calculated with Equation 2. Curve numbers for the fractional AMC values (2¼, 2½ and 2¾) were obtained by interpolating linearly between CN^2 and CN^3. The curve number for each watershed was calculated as an area-weighted average of the curve numbers for the polygons within the watershed.

TABLE 3.3: Runoff Curve Numbers for AMC 2

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 Herbaceus Wetlands	49	69	79	84

3.5.5 HEC-1 Data Files

In the HEC-1 simulations, each watershed was modeled as a single basin. The required inputs for the HEC-1 simulations were as follows:

- Rainfall depth-duration data for specified recurrence interval
- Drainage area
- Runoff curve number
- Lag time

Rainfall depth-duration-frequency data for the selected watersheds were obtained from KDOT's Rainfall Tables for Counties in Kansas (KDOT, 1997), based on the location of the watershed's centroid. KDOT's rainfall tables were linked and added to the attribute table of a digital map of counties in Kansas. The digital map of counties was obtained from ESRI's Data & Maps CD-ROM (ESRI, 1998). Table 3.4 shows an example HEC-1 data file. Table 3.5 shows the watershed characteristics used for the flood simulations.

TABLE 3.4: Example HEC-1 Data File

HEC-1 Input	Comments
ID Basin 12 RUN	Run for Watershed No. 12
IT 5 01JAN00 0000 300	Time specifications
IO 5	Output control
* ******	
KK121111	Simulation ID
BA 3.42	Basin area
PH 50 0 0.43 0.85 1.50 1.70 1.80	Storm data
LS 0 72 0	NRCS loss model: curve number
UD 1.21	NRCS unit hydrograph: lag time
* ******	
KK122112	Simulation ID
BA 3.42	Basin area
PH 50 0 0.43 0.85 1.50 1.70 1.80	Storm data
LS 0 72 0	NRCS loss model: curve number
US 1.21 0.62	Snyder unit hydrograph: lag time and peaking coefficient
* ******	

TABLE 3.5: Watershed Characteristics for Flood Simulations

No.	Station ID	Drainage Area (km^2)	Channel Length (km)	Slope (m/m)	Lag Time (hr)	CN_2	Region
1	6813700	2.32	3.07	0.0120	0.69	85	East
2	6815700	9.57	5.92	0.0045	1.49	84	East
3	6818260	33.40	11.41	0.0071	1.97	76	East
4	6846200	27.32	10.93	0.0074	1.89	73	West
5	6847600	20.28	10.59	0.0033	2.40	73	West
6	6848200	2.75	3.07	0.0094	0.75	74	West
7	6856800	10.32	8.22	0.0037	1.96	81	East
8	6863400	12.45	12.54	0.0032	2.71	72	West
9	6863700	15.79	17.16	0.0026	3.59	73	West
10	6864300	14.16	7.40	0.0046	1.70	75	West
11	6864700	24.84	15.06	0.0033	3.03	73	West
12	6866800	8.85	5.33	0.0067	1.21	72	West
13	6867800	2.79	2.30	0.0288	0.43	79	West
14	6868300	16.76	8.61	0.0062	1.70	74	West
15	6868900	7.52	8.55	0.0073	1.61	75	West
16	6872600	13.92	10.59	0.0039	2.28	73	West
17	6873300	2.27	2.99	0.0111	0.70	73	West
18	6873800	3.72	4.43	0.0091	0.97	72	West
19	6876200	25.49	14.21	0.0043	2.69	76	East
20	6877400	6.43	7.27	0.0054	1.60	84	East
21	6879700	35.06	16.77	0.0021	3.77	85	East
22	6884100	4.18	3.43	0.0121	0.75	82	East
23	6884300	7.50	4.26	0.0099	0.92	80	East
24	6887200	36.27	13.49	0.0072	2.18	77	East
25	6888600	40.70	13.90	0.0037	2.77	80	East
26	6889100	5.36	4.88	0.0045	1.30	85	East
27	6889120	27.29	10.41	0.0032	2.40	84	East
28	6889140	43.59	15.42	0.0026	3.34	83	East
29	6889600	9.95	7.02	0.0041	1.71	85	East
30	6890700	2.18	2.17	0.0112	0.57	75	East
31	6891050	33.81	11.59	0.0068	2.02	79	East
32	6912300	9.44	5.02	0.0061	1.20	78	East
33	6913600	25.90	12.42	0.0024	2.98	83	East
34	6914250	0.95	1.46	0.0233	0.34	76	East
35	6916700	5.38	3.98	0.0075	0.96	80	East
36	6917100	2.30	2.83	0.0072	0.78	74	East
37	6917400	7.28	5.78	0.0066	1.28	77	East
38	7139700	24.24	13.89	0.0026	3.10	73	West
39	7141400	2.24	3.25	0.0046	0.99	72	West
40	7141800	44.54	22.61	0.0025	4.37	73	West
41	7142100	25.86	15.43	0.0022	3.55	73	West
42	7143100	3.81	4.20	0.0039	1.24	79	West
43	7143200	49.07	19.49	0.0022	4.11	75	West
44	7144900	3.79	3.22	0.0051	0.95	74	West
45	7145300	13.11	9.35	0.0027	2.39	77	East
46	7145800	1.03	2.29	0.0092	0.62	81	East
47	7146700	26.45	15.61	0.0029	3.23	82	East

TABLE 3.5: Watershed Characteristics for Flood Simulations (continued)

No.	Station ID	Drainage Area (km^2)	Channel Length (km)	Slope (m/m)	Lag Time (hr)	CN_2	Region
48	7147020	0.45	1.16	0.0112	0.37	84	East
49	7147200	2.28	2.27	0.0099	0.61	84	East
50	7147990	6.48	5.49	0.0096	1.10	79	East
51	7148700	12.99	5.73	0.0126	1.03	72	West
52	7148800	5.53	5.05	0.0072	1.14	78	West
53	7151600	30.33	16.96	0.0040	3.07	74	West
54	7156700	10.43	7.00	0.0073	1.41	73	West
55	7157400	17.42	10.54	0.0074	1.84	73	West
56	7166200	17.64	9.46	0.0038	2.13	81	East
57	7169200	19.48	7.11	0.0057	1.55	79	East
58	7169700	4.67	3.70	0.0088	0.87	78	East
59	7170600	38.82	11.02	0.0034	2.46	78	East
60	7170800	11.11	5.41	0.0050	1.35	80	East
61	7171700	7.99	5.20	0.0090	1.08	79	East
62	7171800	1.39	2.30	0.0314	0.42	81	East
63	7171900	49.89	16.17	0.0041	2.95	78	East
64	7180300	1.50	2.38	0.0090	0.65	79	East
65	7182520	21.42	11.07	0.0023	2.78	82	East
66	7183800	33.97	9.25	0.0034	2.19	81	East

3.6 Regional Climate

3.6.1 Mean Annual Precipitation

The spatial distribution of mean annual precipitation across Kansas is mapped in Figure 3.4. We created this map from mean annual precipitation data for 453 stations located in or near Kansas, which we obtained from the National Climatic Data Center. The period of record was 1971-2000. The contours were interpolated by Kriging.

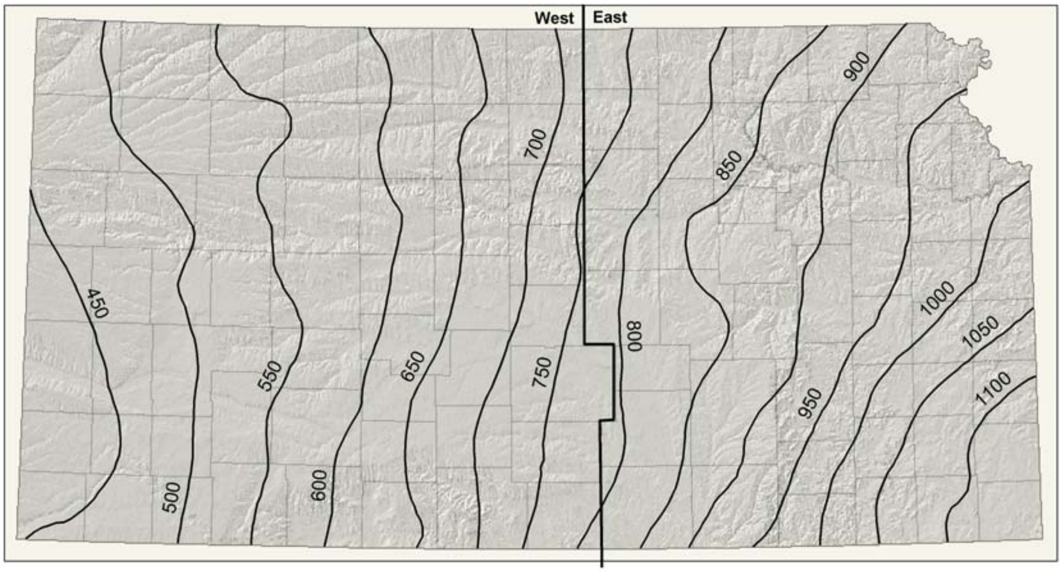

FIGURE 3.4: Mean Annual Precipitation (mm)

3.6.2 Mean Annual Lake Evaporation

The spatial distribution of mean annual lake evaporation across Kansas is shown in Figure 3.4. We developed this map by interpolation from a map of mean annual free water surface evaporation (mean annual evaporation from shallow lakes) published by the National Weather Service (1982). In general, shallow-lake evaporation is a good approximation for potential evapotranspiration.

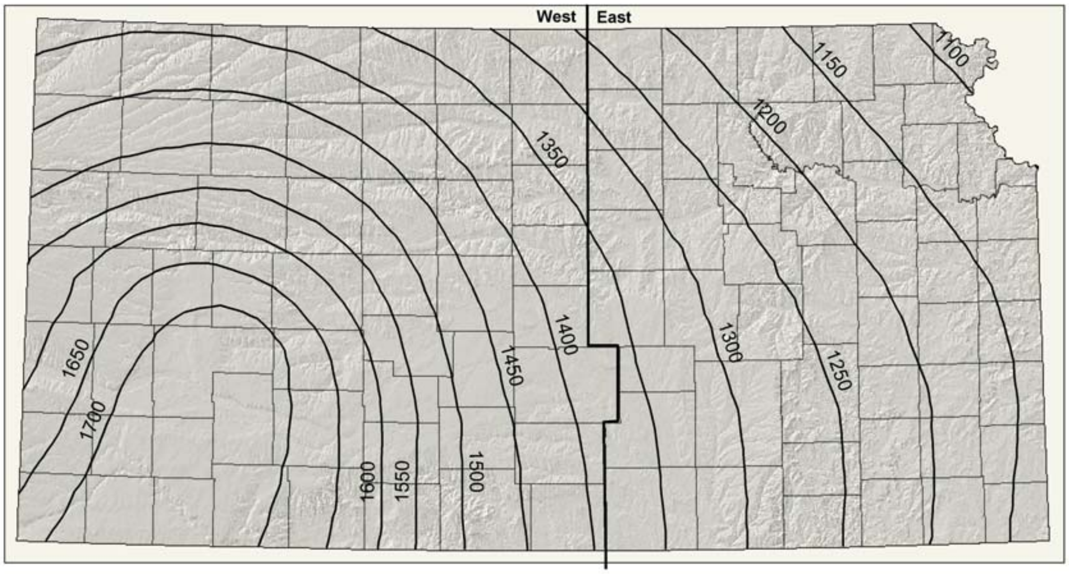

FIGURE 3.5: Mean Annual Free Water Surface Evaporation (mm)

3.6.3 Mean Annual Water Deficit

The mean annual water deficit, defined as the difference between mean annual lake evaporation and mean annual precipitation, provides a general indication of the wetness or dryness of the climate. The spatial distribution of the mean annual water deficit across Kansas is mapped in Figure 3.6. This map was created by subtracting the mean annual precipitation in Figure 3.4 from the mean annual lake evaporation in Figure 3.5.

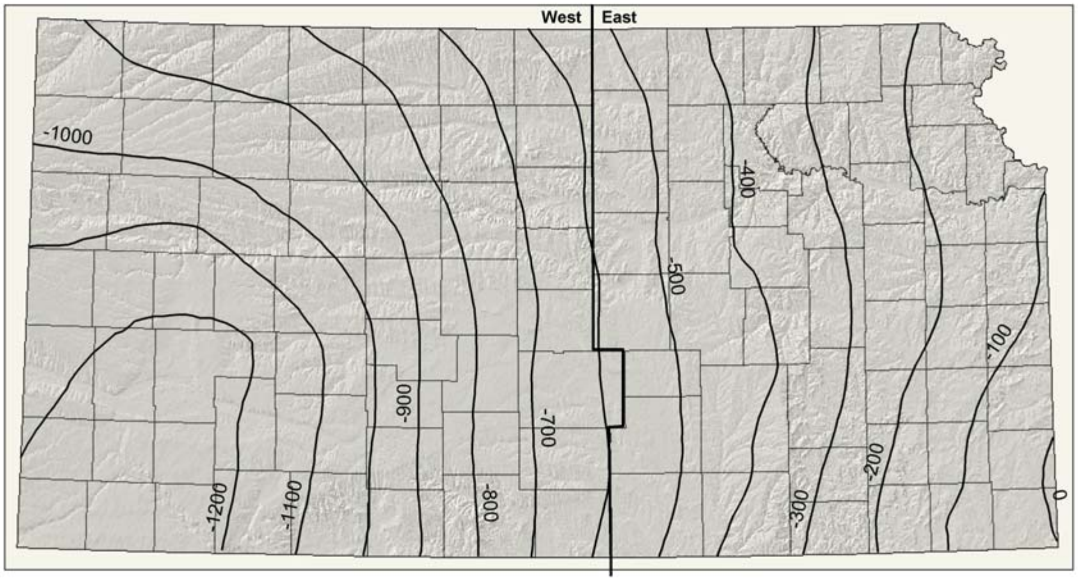

FIGURE 3.6: Annual Surface Water Deficit (mm)

Chapter 4

Test Results

4.1 Regional Analysis

Soils and climate differ greatly across Kansas. The spatial trends run primarily from east to west, as is shown in Figures 3.2, 3.4, 3.5 and 3.6. For these reasons, the test results for the watersheds in eastern and western Kansas were analyzed separately. The dividing line, shown in Figures 3.1 through 3.6, is the 98th meridian (adjusted to county boundaries), as in previous hydrologic studies of Kansas by the USGS and others. Forty of the test watersheds lie in the eastern region and 26 lie in the western region.

We computed the bias in the simulated flows for each region and combination of inputs (recurrence interval, storm duration, antecedent moisture condition and UH model). The bias is defined as the average discrepancy between the simulated flow, Q_s, and the gage-based estimate, Q_g, expressed as a percentage of Q_g. Because the ratio $(Q_s\text{-}Q_g)/Q_g$ is bounded on the low side (by -100% for $Q_s = 0$) but unbounded on the high side, we used a logarithmic averaging scheme. The mean value of Q_s/Q_g was considered to be the inverse logarithm of the mean value of $\log(Q_s/Q_g)$. By subtracting one from this value, we obtained the mean value of $(Q_s\text{-}Q_g)/Q_g$. We also computed the standard error of the simulated flows for each region and combination of inputs. The standard error was defined as standard deviation of the discrepancies between the simulated flows and the gage-based estimates, computed by a logarithmic scheme and expressed as positive and negative percentages of the gage-based estimate. These percentages are $(10^x - 1)\cdot 100$ and $(10^{-x} - 1)\cdot 100$ where x is the standard deviation of $\log(Q_s/Q_g)$.

4.2 Tables of Results

Tables 4.1 through 4.6 provide a concise summary of the test results. Tables 4.1 through 4.4 show the bias in the simulated flows for each region and combination of inputs. Biases between –10 percent and +10 percent are considered acceptable; these values are highlighted. Tables 4.5 and 4.6 show the recommended AMCs for each combination of storm duration, recurrence interval and UH model in each region. The recommended AMCs are the ones with the smallest associated biases. If all AMCs between 2 and 3 have associated biases larger than 10 percent, then no recommendation is shown. Tables 4.5 and 4.6 show the biases and standard errors for flows simulated with the recommended AMCs.

TABLE 4.1: Bias in Simulated Flows for Eastern Kansas, NRCS UH Model

Recurrence interval (yr)	Storm duration (hr)	Bias between simulation and gage estimates (%)				
		AMC 2	AMC 2¼	AMC 2½	AMC 2¾	AMC 3
2	3	-21%	-4%	16%	38%	63%
	6	0%	20%	41%	64%	91%
	12	21%	41%	63%	87%	112%
	24	42%	63%	84%	106%	130%
5	3	-21%	-9%	4%	18%	33%
	6	-5%	8%	21%	35%	50%
	12	10%	23%	36%	49%	63%
	24	24%	36%	48%	60%	72%
10	3	-24%	-14%	-4%	7%	18%
	6	-10%	0%	10%	21%	32%
	12	2%	12%	22%	31%	41%
	24	13%	22%	31%	39%	48%
25	3	-29%	-21%	-13%	-5%	3%
	6	-17%	-9%	-2%	6%	14%
	12	-7%	0%	7%	14%	21%
	24	1%	8%	14%	20%	26%
50	3	-32%	-26%	-19%	-13%	-6%
	6	-22%	-16%	-9%	-3%	3%
	12	-13%	-7%	-2%	4%	9%
	24	-7%	-1%	4%	8%	13%
100	3	-35%	-30%	-24%	-19%	-13%
	6	-26%	-21%	-16%	-10%	-5%
	12	-19%	-14%	-9%	-5%	0%
	24	-13%	-9%	-5%	-1%	3%

TABLE 4.2: Bias in Simulated Flows for Eastern Kansas, Snyder UH Model

Recurrence interval (yr)	Storm duration (hr)	Bias between simulation and gage estimates (%)				
		AMC 2	AMC 2¼	AMC 2½	AMC 2¾	AMC 3
2	3	-31%	-15%	2%	21%	44%
	6	-12%	5%	24%	44%	68%
	12	6%	24%	44%	64%	87%
	24	25%	44%	63%	82%	103%
5	3	-31%	-20%	-9%	3%	17%
	6	-16%	-5%	7%	19%	32%
	12	-3%	8%	20%	32%	44%
	24	9%	20%	31%	42%	53%
10	3	-33%	-25%	-16%	-6%	4%
	6	-21%	-12%	-3%	6%	16%
	12	-10%	-1%	7%	16%	25%
	24	0%	8%	16%	24%	31%
25	3	-37%	-31%	-24%	-17%	-9%
	6	-27%	-20%	-14%	-7%	0%
	12	-18%	-12%	-5%	1%	7%
	24	-11%	-5%	1%	6%	12%
50	3	-40%	-35%	-29%	-23%	-17%
	6	-31%	-26%	-20%	-15%	-9%
	12	-24%	-18%	-13%	-8%	-3%
	24	-18%	-13%	-8%	-4%	0%
100	3	-43%	-38%	-33%	-29%	-23%
	6	-35%	-30%	-26%	-21%	-16%
	12	-28%	-24%	-20%	-16%	-12%
	24	-23%	-19%	-15%	-12%	-9%

TABLE 4.3: Bias in Simulated Flows for Western Kansas, NRCS UH Model

Recurrence interval (yr)	Storm duration (hr)	Bias between simulation and gage estimates (%)				
		AMC 2	AMC 2¼	AMC 2½	AMC 2¾	AMC 3
2	3	-8%	32%	80%	136%	206%
	6	22%	68%	122%	185%	260%
	12	48%	98%	157%	224%	303%
	24	74%	129%	192%	262%	343%
5	3	2%	29%	59%	91%	130%
	6	24%	54%	86%	121%	161%
	12	46%	78%	112%	148%	189%
	24	65%	98%	134%	170%	210%
10	3	-1%	20%	42%	67%	94%
	6	17%	40%	64%	90%	118%
	12	36%	60%	86%	111%	139%
	24	52%	76%	102%	127%	154%
25	3	-8%	8%	25%	43%	62%
	6	7%	24%	42%	60%	80%
	12	23%	41%	59%	77%	96%
	24	35%	53%	71%	88%	106%
50	3	-13%	0%	14%	29%	44%
	6	0%	14%	29%	43%	59%
	12	14%	29%	43%	57%	72%
	24	25%	39%	53%	67%	80%
100	3	-18%	-6%	5%	17%	30%
	6	-6%	6%	18%	30%	42%
	12	7%	18%	30%	42%	53%
	24	15%	27%	38%	49%	60%

TABLE 4.4: Bias in Simulated Flows for Western Kansas, Snyder UH Model

Recurrence interval (yr)	Storm duration (hr)	Bias between simulation and gage estimates (%)				
		AMC 2	AMC 2¼	AMC 2½	AMC 2¾	AMC 3
2	3	-19%	16%	58%	107%	168%
	6	7%	47%	95%	149%	216%
	12	29%	73%	125%	184%	253%
	24	52%	101%	156%	217%	288%
5	3	-11%	13%	39%	68%	101%
	6	9%	34%	63%	94%	128%
	12	28%	55%	86%	117%	153%
	24	45%	74%	105%	137%	172%
10	3	-14%	5%	25%	46%	70%
	6	3%	23%	44%	66%	91%
	12	19%	40%	62%	85%	110%
	24	33%	55%	77%	100%	124%
25	3	-19%	-5%	10%	25%	42%
	6	-6%	9%	24%	40%	57%
	12	8%	23%	39%	55%	72%
	24	19%	34%	50%	66%	81%
50	3	-24%	-12%	0%	13%	26%
	6	-12%	0%	13%	26%	39%
	12	0%	13%	25%	38%	51%
	24	9%	22%	34%	46%	59%
100	3	-28%	-18%	-8%	3%	14%
	6	-18%	-7%	3%	14%	25%
	12	-7%	4%	14%	24%	35%
	24	1%	12%	22%	31%	41%

TABLE 4.5: Recommended Antecedent Moisture Conditions for Eastern Kansas

a. Recommended AMC

NRCS UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3	2 ¼	2 ½	2 ½	3	3	
6	2	2	2 ¼	2 ½	2 ¾	
12			2	2 ¼	2 ½	3
24				2	2 ¼	2 ¾

Snyder UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3	2 ½	2 ¾	3	3		
6	2 ¼	2 ¼	2 ½	3	3	
12	2	2	2 ¼	2 ¾	3	
24		2	2	2 ½	3	3

b. Bias in Flows Simulated with Recommended AMC

NRCS UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3	-4%	4%	-4%	3%	-6%	
6	0%	-5%	0%	-2%	-3%	
12			2%	0%	-2%	0%
24				1%	-1%	-1%

Snyder UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3	2%	3%	4%	-9%		
6	5%	-5%	-3%	0%	-9%	
12	6%	-3%	-1%	1%	-3%	
24		9%	0%	1%	0%	-9%

c. Standard Errors for Flows Simulated with Recommended AMC

NRCS UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3	+53%/-35%	+43%/-30%	+42%/-29%	+43%/-30%	+46%/-31%	
6	+53%/-35%	+43%/-30%	+41%/-29%	+43%/-30%	+46%/-31%	
12			+40%/-29%	+42%/-30%	+45%/-31%	+49%/-33%
24				+42%/-30%	+45%/-31%	+49%/-33%

Snyder UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3	+52%/-34%	+43%/-30%	+42%/-30%	+44%/-30%		
6	+52%/-34%	+42%/-30%	+41%/-29%	+43%/-30%	+46%/-32%	
12	+51%/-34%	+42%/-29%	+40%/-29%	+43%/-30%	+46%/-31%	
24		+41%/-29%	+40%/-29%	+43%/-30%	+46%/-31%	+49%/-33%

TABLE 4.6: Recommended Antecedent Moisture Conditions for Western Kansas

a. Recommended AMC

NRCS UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3	2	2	2	2 ¼	2 ¼	2 ½
6				2	2	2 ¼
12						2
24						

Snyder UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3			2 ¼	2 ¼	2 ½	2 ¾
6	2	2	2	2	2 ¼	2 ½
12				2	2	2 ¼
24					2	2

b. Bias in Flows Simulated with Recommended AMC

NRCS UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3	-8%	2%	-1%	8%	0%	5%
6				7%	0%	6%
12						7%
24						

Snyder UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3			5%	-5%	0%	3%
6	7%	9%	3%	-6%	0%	3%
12				8%	0%	4%
24					9%	1%

c. Standard Errors for Flows Simulated with Recommended AMC

NRCS UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3	+74%/-43%	+65%/-39%	+69%/-41%	+78%/-44%	+86%/-46%	+94%/-48%
6				+77%/-44%	+86%/-46%	+95%/-49%
12						+93%/-48%
24						

Snyder UH Model

Duration (hr)	Recurrence Interval (yr)					
	2	5	10	25	50	100
3			+70%/-41%	+78%/-44%	+85%/-46%	+92%/-48%
6	+74%/-42%	+64%/-39%	+68%/-41%	+78%/-44%	+86%/-46%	+94%/-48%
12				+76%/-43%	+85%/-46%	+94%/-48%
24					+84%/-46%	+93%/-48%

4.3 Storm Duration, AMC and Recurrence Interval

Longer storm durations and/or higher AMCs are needed to simulate floods with longer recurrence intervals. Extreme floods result from heavy rainfall onto saturated or nearly saturated soils. The higher the AMC and the longer the storm duration, the wetter the soil during the period of heaviest rainfall. The effect of increasing the storm duration is similar to the effect of increasing the AMC. Different combinations of storm duration and AMC will produce the same peak flows. Figure 4.1 provides an example. The three curves represent the combinations of storm duration and AMC that will produce flows with recurrence intervals of 10, 25 and 50 years in eastern Kansas.

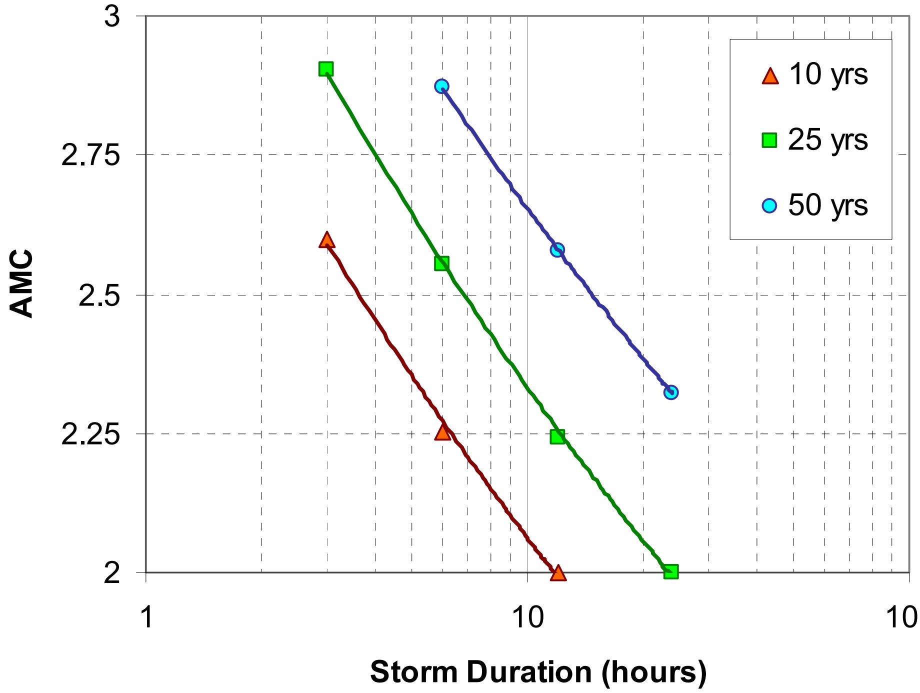

FIGURE 4.1: Recommended AMC vs. Storm Duration for Selected Recurrence Intervals (Eastern Kansas, NRCS UH Model)

4.4 Regional Differences: Eastern and Western Kansas

The test results for the eastern and western regions differ markedly. The recommended storm durations are shorter and the recommended AMCs are lower in the west than in the east. For example, consider the simulation of a 100-year flood using the NRCS UH model. The recommended inputs for eastern Kansas are a 12-hour storm with AMC 3 or a 24-hour storm with AMC 2¾, while the recommended inputs for western Kansas are a 3-hour storm with AMC 2½, a 6-hour storm with AMC 2¼ or a 12-hour storm with AMC 2. These results indicate that, during periods of extreme rainfall, losses are typically much higher in the west than in the east. Losses are higher in the west because soils are more permeable (Figure 3.2) and drier on average. Soils are drier because the region receives much less total precipitation (Figure 3.4) and the evaporative demand is higher (Figure 3.5). The standard errors of the flow estimates for the western region are much larger than those for the eastern region.

4.5 Comparison of Unit Hydrograph Models

The recommended storm durations and AMCs differ according to the UH model used in the simulation. The Snyder UH model requires longer storm durations and/or higher AMCs than the NRCS UH model. The Snyder UH model is not recommended for simulations of 100-year floods in eastern Kansas because a storm duration in excess of 24 hours would be needed to obtain an unbiased estimate of the 100-year flow. The Snyder UH model produces lower flows than the NRCS UH model because the Snyder unit hydrographs had a less "peaky" shape than the NRCS unit hydrographs. The Snyder unit hydrographs were assigned peaking coefficients of 0.62, based on the results of a calibration study by McEnroe and Zhao (1999).

4.6 Flood Hydrograph Simulation versus USGS Regression Equations

Flood hydrograph simulation and the USGS regression equations are alternative methods for estimating design flows. To obtain a rough comparison of the accuracy of these two methods, we applied the USGS regression equations for Kansas (Rasmussen and Perry, 2000) to the selected gaged watersheds. Tables 4.7 and 4.8 show the bias and standard error of the regression estimates, relative to the gage-based estimates, for each region and recurrence interval. The regression estimates for the eastern region are essentially unbiased, but the regression estimates for the western region exhibit a strong bias toward overestimation. These results can be compared with the results for flood hydrograph simulation (Tables 4.5 and 4.6). The flows obtained by simulation with the recommended procedures and inputs exhibit minimal bias in both regions. The two methods have similar standard errors. The standard errors for both methods are much larger in the western region than in the eastern region.

TABLE 4.7: Bias and Standard Errors for USGS Regression Equations Applied to 40 Selected Watersheds in Eastern Kansas

	Recurance Interval (yr)					
	2	5	10	25	50	100
Average overestimation	0%	2%	4%	3%	2%	2%
Standard Errors	+47%/-32%	+43%/-30%	+45%/-31%	+49%/-33%	+52%/-34%	+56%/-36%

TABLE 4.8: Bias and Standard Errors for USGS Regression Equations Applied to 26 Selected Watersheds in Western Kansas

	Recurrence Interval (yr)					
	2	5	10	25	50	100
Average overestimation	8%	16%	21%	22%	22%	23%
Standard Errors	+71%/-41%	+67%/-40%	+72%/-42%	+82%/-45%	+91%/-48%	+99%/-50%

4.7 Applicability of Recommended Inputs

The recommended storm durations and antecedent moisture conditions in Tables 4.5 and 4.6 are applicable to watersheds in Kansas with drainage areas up to 50 km^2. These recommendations are appropriate for urban as well as rural watersheds, provided that the inputs to the loss model and the hydrograph model account for the effects of urban development. They are also appropriate for simulation models with multiple subbasins linked by channel routing, and for simulation models that include reservoir routing at small lakes.

Chapter 5

Recommendations for the KDOT Design Manual

The forthcoming revision of Volume I, Part C of the KDOT Design Manual, "*Elements of Drainage and Culvert Design,"* will include guidelines for design-flow estimation by flood hydrograph simulation. We recommend that this section of the Design Manual include the following standard procedures:

Software:	HEC-1 or HEC-HMS
Loss model:	NRCS curve-number model
Hydrograph model:	NRCS unit hydrograph model
Lag times:	Regression equations for lag times of rural watersheds (McEnroe and Zhao, 1999) and urban and developing watersheds (McEnroe and Zhao, 2001)
Design storm:	HEC hypothetical frequency-based storm
Storm duration:	From Table 5.1
Antecedent moisture condition:	From Table 5.1

TABLE 5.1: Recommended Storm Durations and Antecedent Moisture Conditions for KDOT Design Manual

	Eastern Kansas		**Western Kansas**	
Recurrence Interval (years)	**Storm Duration (hours)**	**AMC**	**Storm Duration (hours)**	**AMC**
2	6	2	3	2
5	6	2	3	2
10	12	2	3	2
25	24	2	6	2
50	24	2¼	6	2
100	24	2¾	12	2

In the interest of simplicity and consistency, these standard procedures specify a single UH model and a single combination of storm duration and AMC for each recurrence interval and region. The test results summarized in Tables 4.5 and 4.6 indicate that these procedures and inputs will produce acceptable design flows. However, the other combinations of inputs listed in these two tables will also yield acceptable results. We selected the NRCS UH model because it is suitable for the entire range of conditions tested, whereas the Snyder UH model with $C_p = 0.62$ requires a storm duration in excess of 24 hours for 100-year floods in eastern Kansas.

Chapter 6

Conclusions

Flood hydrograph simulation with appropriate inputs can yield reasonable estimates of design flows. Our tests indicate that the procedures and inputs listed in Section 2.5 and Tables 4.5 and 4.6 work well for watersheds in Kansas with drainage areas up to 50 km^2. The standard errors of the simulated flows are larger in western Kansas than in eastern Kansas. Flood hydrograph simulation with the recommended inputs is approximately as accurate as the USGS regression equations in eastern Kansas and more accurate than the USGS regression equations in western Kansas. The USGS regression equations appear to overestimate design flows in western Kansas. Flood hydrograph simulation is subject to fewer limitations than the USGS regression equations and the rational method. It can be applied to urban watersheds and regulated streams.

The recommended storm durations and antecedent moisture conditions depend on the region, recurrence interval and UH model. The storm durations are shorter and the AMCs are lower in the western region than in the eastern region. Longer storm durations and/or higher AMCs are needed for higher recurrence intervals. The Snyder UH model (with $C_p = 0.62$) requires longer storm durations and/or higher AMCs than the NRCS UH model.

We recommend the simplified guidelines for flood hydrograph simulation in Chapter 5 for inclusion in the KDOT Design Manual, Volume I, Part C. These guidelines specify the NRCS UH model and a single combination of storm duration and AMC for each recurrence interval and region.

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