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Estimating the Discharge for Ordinary High Water Levels in Kansas

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The University of Kansas

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16 Abstract

The water resource design community in Kansas, including the Kansas Department of Transportation (KDOT), is required to obtain appropriate permits for construction projects. Projects that involve stream modification, including drainage structures, must define the Ordinary High Water (OHW) level or mark and the related discharge (Q_{OHW}) for compliance and permitting purposes.

The purpose of this report is to provide guidance on both the definition of the OHW level and the hydrologic estimation of the discharge responsible for the OHW level in rural Kansas streams. This report provides two methods for the hydrologic estimation of the discharge responsible for the ordinary high water level in Kansas: a regression-based approach and a HEC-HMS flood hydrograph simulation method.

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and

THE UNIVERSITY OF KANSAS
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PREFACE

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

NOTICE

DISCLAIMER

Abstract

The water resource design community in Kansas, including the Kansas Department of Transportation (KDOT), is required to obtain appropriate permits for construction projects. Projects that involve stream modification, including drainage structures, must define the Ordinary High Water (OHW) level or mark and the related discharge (Q_{OHW}) for compliance and permitting purposes.

The OHW level or mark is used by the United States Army Corps of Engineers (USACE) to determine jurisdictional and regulatory boundaries over non-tidal waters under Section 404 of the Clean Water Act and under Sections 9 and 10 of the Rivers and Harbors Act of 1899 (USACE 2005).

The purpose of this report is to provide guidance on both the definition of the OHW level and the hydrologic estimation of the discharge responsible for the OHW level in rural Kansas streams. This report provides two methods for the hydrologic estimation of the discharge responsible for the ordinary high water level in Kansas: a regression-based approach in Chapter 3 and a HEC-HMS flood hydrograph simulation method in Chapter 4.

Both methods presented in this report rely on the functional equivalence between the bankfull stage, as defined by Rosgen (1996) and Harrelson et al. (1994), and the OHW level as defined by USACE (2005). The list of reliable indicators of the OHW in USACE (2005) are nearly identical to the physical characteristics that define the bankfull stage in self-formed, natural channels.

Research by McEnroe et al. (2009) indicates that the average recurrence interval (ARI) for the bankfull flow in Kansas is 0.545 years. As such, the frequency of the OHW flow in Kansas streams can be estimated as an event with ARI = 0.545 years or 6.5 months. The 6.5-

month event has an annual exceedance probability (AEP) of 0.84 and may be referred to as the 84%-chance event.

This frequency-based definition of the Q_{OHW} is supported by USACE (2005) which states that the OHW level should be an indication of 'regular or frequent' high-water levels. The 6.5-month event will occur about twice per year, and will be equaled or exceeded in approximately 84% of all years.

USACE (2005) states a clear preference for the use of on-site, physical indicators of the OHW. Where possible, two or more of the characteristics in Table 2-2 should be used to identify the OHW in Kansas streams. The hydrologic methods presented in Chapters 3 and 4 can be used as a check on field estimates, or in lieu of field determination where physical indicators are absent, misleading or inconclusive.

Acknowledgments

This project was supported by the Kansas Department of Transportation (KDOT) through the Kansas Transportation Research and New Developments (K-TRAN) Program. James Richardson, P.E., and Brad Rognlie, P.E., of KDOT served as the project monitors. Michael Orth, P.E., of KDOT also provided valuable guidance. The authors sincerely appreciate the contributions of these individuals.

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Chapter 1: Introduction

The water resource design community in Kansas, including the Kansas Department of Transportation (KDOT), is required to obtain appropriate permits for construction projects. Projects that involve stream modification, including drainage structures, must define the Ordinary High Water (OHW) level or mark and the related discharge (Q_{OHW}) for compliance and permitting purposes.

The OHW level or mark is used by the United States Army Corps of Engineers (USACE) to determine jurisdictional and regulatory boundaries over non-tidal waters under Section 404 of the Clean Water Act and under Sections 9 and 10 of the Rivers and Harbors Act of 1899 (USACE 2005). The USACE defines the OHW in Regulatory Guidance Letter No. 05-05 published December 7, 2005 (USACE 2005) by citing 33 CFR 328.2(e):

> "The term ordinary high water mark means the line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas."

USACE Regulatory Letter No. 05-05 provides a framework for the definition and determination of the OHW level using physical characteristics (discussed in Chapters 2 of this report) but acknowledges that physical characteristics may in some cases be "inconclusive, misleading, unreliable, or otherwise not evident" (USACE 2005). In such cases, the USACE provides for the use of a number of other approaches for reliable determination of the OHW level, including "lake and stream gage data, elevation data, spillway height, flood predictions, historic records of water flow, and statistical evidence" (USACE 2005).

The purpose of this report is to provide guidance on both the definition of the OHW level and the hydrologic estimation of the discharge responsible for the OHW level in rural Kansas streams. Chapter 2 examines the definition of the OHW with specific attention to self-formed natural channels. Chapter 3 presents a regional regression equation for determination of the discharge responsible for the OHW level in rural Kansas Streams. Chapter 4 presents an alternative HEC-HMS method that can be used to estimate the Q_{OHW}. Chapter 5 summarizes and concludes the report.

Chapter 2: Definition of the Ordinary High Water Level

The purpose of this chapter is to state the definition of the OHW level presented by USACE Regulatory Guidance Letter 05-05, and to use the criteria set forth in that document to establish an appropriate frequency-based definition of the Q_{OHW} for rural Kansas streams.

2.1 USACE Regulatory Guidance Letter 05-05

USACE (2005) presents a list of physical characteristics to be considered when determining the ordinary high water level (OHWL) or ordinary high water mark (OHWM) for a stream. This list is presented in Table 2-1:

TABLE 2-1: Physical Characteristics of the Ordinary High Water Level Presented

Natural line impressed on the bank	Sediment sorting
Shelving	Leaf litter disturbed or washed away
Changes in the character of soil	Scour
Destruction of terrestrial vegetation	Deposition
Presence of litter and debris	Multiple observed flow events
Wracking	Bed and banks
Vegetation matted down, bent, or absent	Water staining
	Change in plant community

Source: USACE (2005)

USACE (2005) acknowledges that the list in Table 2-1 is not exhaustive, and stresses that there is no set of required physical characteristics. The regulatory letter advises that two or more characteristics be used in combination to define the OHW level unless one physical characteristic is sufficiently distinctive.

USACE (2005) stresses that districts should consider evidence of "ordinary high water events, which occur on a regular or frequent basis." The determination of the OHW level should not be influenced by infrequent, "extraordinary events." The example given in USACE (2005) is "a litter or wrack line resulting from a 200-year flood event would in most cases not be considered evidence of an OHWM."

2.2 Comparison of Ordinary High Water and Bankfull-Flow Characteristics

Many of the characteristics in Table 2-1 are temporary indications of recent high-water levels. Such physical characteristics may represent the high water level from a recent large flood, and are therefore not reliable indicators of the *ordinary* high water level.

Table 2-2 lists the reliable, more permanent indicators of the OHW level in Kansas from Table 2-1 and provides a brief description of each indicator. There is a strong indication in the literature that the most reliable characteristics of the OHW level are variations in vegetation and soil in and near the stream channel.

TABLE 2-2: Reliable Physical Characteristics of the Ordinary High Water Level in Kansas

Physical Characteristic	What to Look for:
Change in plant community	A change in plant community from species that tolerate occasional-to-frequent inundation to species that do not tolerate frequent inundation.
Changes in the character of soil Sediment sorting Scour Deposition	In a fluvial environment, the action of flowing water will tend to erode fine-grained sediment, leaving behind coarser-grained particles. An abrupt transition in grain size distribution can serve as an indication of the OHW level (North Dakota 2007). The tops of depositional features (e.g., point bars) will usually be below the OHW level (Olson and Stockdale 2010).
Bed and banks	The combined forces of sediment sorting, scour, and deposition tend to form a natural channel in an alluvial system. In an undisturbed, self-formed stream, the top of the stream bank is a reliable physical indicator of the OHW. Many stream channels in Kansas have experienced historical degradation or incision. On incised streams, the top of the bank can be much higher than the OHW.
Multiple observed flow events	USACE (2005) does not clarify what frequency of flow events constitutes the OHW, but it is clear that the OHW level should be associated with frequent high flows and not with extraordinary floods.
Natural line impressed on the bank Water staining	Frequent high water levels may leave a distinct line impressed on the channel bank and/or may leave stain marks on rock, culverts, bridge piers, or other stationary objects. Olson and Stockdale (2010) state that the interpretation of water marks should be undertaken with caution, as extraordinary high water may leave marks as well. If multiple stain lines exist, the darkest line is probably below the OHW level (Olson and Stockdale 2010).
Shelving	Shelving occurs primarily in incised channels when frequent high water erodes out soil from underneath the top of bank, leaving a shelf of soil. The bottom of this suspended shelf can serve as an indication of the OHW level (North Dakota 2007).

2.3 Bankfull Flow Level and the Ordinary High Water Level

The physical characteristics listed in Table 2-2 compare well with the guidelines for selecting bankfull levels according to the Rosgen stream characterization approach. Rosgen's bankfull flow indicators are (Rosgen 1996):

- The presence of a floodplain at the elevation of incipient flooding.
- The elevation associated with the top of the highest depositional features (e.g., point bars, central bars within the active channel). These depositional features are especially good stage indicators for channels in the presence of terraces or adjacent colluvial slopes.
- A break in slope of the banks and/or a change in the particle size distribution, (since finer material is associated with deposition by overflow, rather than deposition of coarser material within the active channel).
- Evidence of an inundation feature such as small benches.
- Staining of rocks.
- Exposed root hairs below an intact soil layer indicating exposure to erosive flows.
- Lichens and – for some stream types and locales – certain riparian vegetation species.

The United States Department of Agriculture (USDA) Forest Service lists similar bankfull indicators (Harrelson et al. 1994), which are likely based on the Rosgen methodology:

- The height of depositional features (especially the top of the point bar, which defines the lowest possible level for bankfull stage).
- A change in vegetation (especially the lower limit of perennial species).
- Slope or topographic breaks along the bank; a change in the particle size of bank material, such as the boundary between coarse cobble or gravel with fine-grained sand or silt.
- Undercuts in the bank, which usually reach an interior elevation slightly below bankfull stage
- Stain lines or the lower extent of lichens on boulders.

The physical characteristics listed by Rosgen (1996) and Harrelson et al. (1994) for the determination of bankfull level agree remarkably well with the reliable physical indicators of the OHW level cited by the USACE (2005). Given that the reliable physical indicators of the OHW map directly to indicators of bankfull flow, it is evident that these two water levels are one and the same, and that the discharge responsible for bankfull flow is equal to the discharge responsible for the ordinary high water level (Q_{OHW}).

It should be stressed that the bankfull designations described by Rosgen (1996) and Harrelson et al. (1994) only apply to undisturbed, self-formed natural channels. These physical characteristics may not be reliable indicators of the bankfull stage or the OHW level in incised or otherwise degraded channels. In an incised system, the channel capacity may be far in excess of the Q_{OHW} and the natural $Q_{bankfull}$. This may be apparent in a field survey if depositional features, shelving, and/or a transition from terrestrial vegetation point to an OWH level below the top of the banks of the stream channel. In such cases, the hydrologic methodology presented in this report may be helpful to confirm that the OHW level is correctly identified in the field.

Physical indicators of the OHW or bankfull level are qualitative in nature and require interpretation of the field evidence by an experienced survey crew. In many cases, physical evidence for the OHW may be missing or indeterminate. This is especially true in highly disturbed systems that have experienced recent degradation or incision, but may also be the case in channels that have experienced recent, extraordinary high-water events.

In such cases, a hydrologic estimate of the discharge responsible for the OHW can provide a useful check against the field evidence. It can also be used in lieu of field evidence where such evidence is deemed unreliable or inconclusive.

The most reasonable approach to hydrologic estimation of the discharge responsible for the OHW (the Q_{OHW}) involves estimating the frequency of events that produce the physical indicators discussed earlier in this section.

2.4 Frequency of the Ordinary High Water Level

It is important to clarify several often-confused terms used to describe streamflow frequency. The terms *return period* and *recurrence interval* are often used to describe the frequency of hydrologic events. There are two underlying definitions of return period or recurrence interval that are functionally equivalent for large, infrequent flood events (greater than 10 years). However, the difference between these definitions is critical for more frequency events. In order to be as clear as possible, this report adopts the following definitions:

Annual Recurrence Interval (ARI): The average period of time between independent events that equal or exceed a specified magnitude. For example, an event with an ARI of 3.8 years will be equaled or exceeded, on average, once every 3.8 years.

Annual Exceedance Probability (AEP): The probability that at least one event that equals or exceeds a specified magnitude will occur in any given year. For example, and event with an AEP = 0.01 has only a 1% chance of being equaled or exceeded in any given year.

It is important to note that the ARI is NOT equal to 1/AEP. Traditionally, KDOT has used the definition of return period, T = 1/AEP for flood events. This definition of return period is based on the annual maximum series. Since the term *return period* can be used to mean either the ARI or 1/AEP, its use is avoided in this report wherever possible.

McEnroe et al. (2009) used a geomorphic dataset of stable, gaged streams to evaluate the average recurrence interval of bankfull flow in Kansas streams. The geomorphic dataset was assembled by The Watershed Institute (TWI) with funding provided by the Kansas Water Office and the United States Environmental Protection Agency (US EPA) (Emmert and Hase 2001).

McEnroe et al. (2009) extracted 46 stable reference reaches near United State Geological Survey (USGS) gages from this geomorphic dataset for further evaluation. Using this dataset, McEnroe et al. (2009) found that the bankfull flow for a natural, self-formed channel has an annual exceedance probability (AEP) of 0.84 (1/AEP = 1.19 years). The streams studied in McEnroe et al. (2009) had bankfull discharges that ranged from ARI of less than 2.6 months to 13.5 months (AEP ranging from 0.59 to over 0.99). The average recurrence interval (ARI) for this event is 0.545 years or 6.5 months. In other words, the stream discharge responsible for the bankfull formation (the $Q_{bankfull}$) occurs, on average, about twice per year and occurs in approximately 84% of all years.

2.5 Conclusion

The USACE (2005) designates physical indicators of the OHW. Table 2-2 presents a subset of the indicators listed in USACE (2005) that are reliable physical indicators that are not highly influenced by recent extraordinary flood events. When possible, two or more of these physical indicators should be used to identify the elevation of the OHW level in a stream channel.

The physical indicators listed by USACE (2005) coincide with the Rosgen (1996) and USDA Forest Service (Harrelson et al. 1994) characteristics of bankfull stage for self-formed, natural channels that have not experienced significant degradation or incision. Given the high level of agreement between the characteristics for bankfull stage and the OHW level, these two characteristic flow levels can be considered functionally equivalent. Therefore we recommend that $Q_{OHW} = Q_{bankfull}$.

Physical indicators may be misleading in cases where a channel is unstable or in a watershed that has undergone rapid change. Use of a frequency-based definition of the Q_{OHW}

allows a consistent, quantitative approach that is not subject to many of the uncertainties present in a field-based determination.

Prior research has indicated that the frequency of bankfull flow in Kansas has an average recurrence interval (ARI) of 6.5 months and an annual exceedance probability (AEP) of 0.84 (1/AEP = 1.19 years). Since we recommend that $Q_{OHW} = Q_{bankfull}$, where physical evidence of the OHW is absent or indeterminate, we recommend estimating the Q_{OHW} as the stream discharge that has an ARI of 6.5 months. The AEP for this event is 0.84 and the return period (defined here as T = 1/AEP) is 1.19 years (which may be rounded off to 1.2 years).

Chapter 3: Estimating the Q_{OHW} Using Regional Regression Analysis

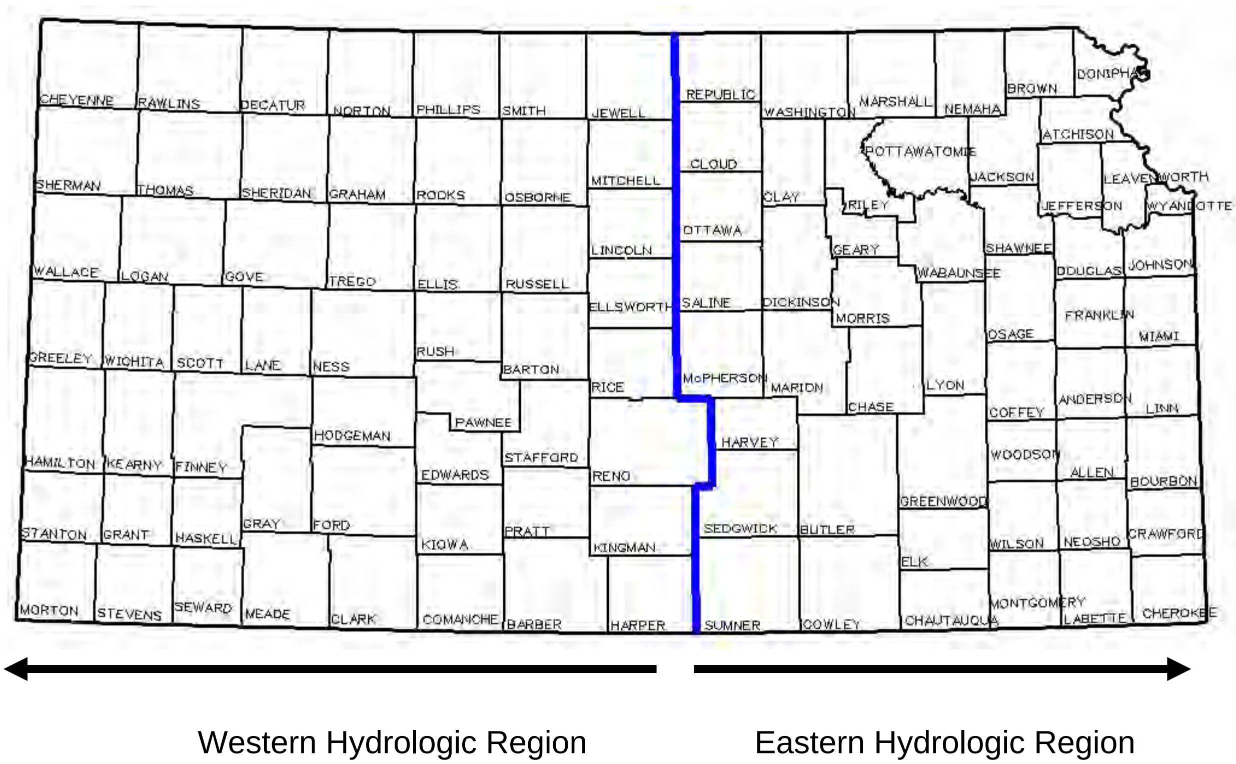
This chapter presents the methodology and results of a regional regression analysis for the determination of the Q_{OHW} in Kansas. As established in Chapter 2, the Q_{OHW} in Kansas is equivalent to the bankfull flow for an undisturbed, self-formed alluvial stream. The annual exceedance probability (AEP) of Q_{OHW} (the probability that Q_{OHW} will be equaled or exceeded in any given year) is estimated as 0.84. The average recurrence interval (ARI) for bankfull flow and for the Q_{OHW} in Kansas is approximately 0.545 years, or 6.5 months.

3.1 Dataset

The dataset for this project consisted of 120 gaged watersheds in Kansas. Gages were selected that met the following criteria:

1. Record length greater than or equal to 10 years.
2. Watershed area less than 100 mi^2 for western Kansas, and less than 30 mi^2 for eastern Kansas. See Figure 3-1 for the definition of eastern and western Kansas.
3. Rural land cover.
4. No significant regulation by flood control reservoirs.

The 120 gaged watersheds are listed in Tables A-1 through A-4 in Appendix A.



(Source: McEnroe et al. 2013a)

FIGURE 3-1: Western and Eastern Hydrologic Regions of Kansas

3.2 Methodology

Data analysis followed the same steps outlined in K-TRAN: KU-12-4 (McEnroe et al. 2013). A flood frequency analysis was conducted for each station using the USACE's Hydrologic Engineering Center-Statistical Software Package (HEC-SSP) (Brunner and Fleming 2010). HEC-SSP implements the full flood-frequency procedure outlined in Bulletin 17B (Interagency Advisory Committee on Water Data 1981). HEC-SSP was used to estimate the Q_{OHW} for each site, using the approximation $Q_{OHW} = Q_{84\%}$.

Watershed characteristics were determined for each basin using the same approaches detailed in McEnroe et al. (2013). Table 3-1 presents the list of characteristics used in the regression analysis.

TABLE 3-1: Watershed Characteristics Considered in this Study

Characteristic	Units	Description
A	mi^2	Total watershed area (including non-contributing areas)
L	mi	Length of the main channel extended to the watershed boundary
Sl	ft/mi	Slope of the main channel, measured between points 10% and 85% along the channel from the watershed outlet to the drainage divide
Sh	none	Basin shape factor (L^2/A)
SP	in./hr	Mean soil permeability of the entire soil profile
t_c	hr	Watershed time of concentration
i_1	in./hr	Rainfall intensity for duration = t_c and average recurrence interval (ARI) = 1 year
$A \cdot i_1$	$mi^2 \cdot$ in./hr	Product of the watershed area and rainfall intensity
MAP	in.	Mean annual precipitation

Watershed area (A), channel length (L), and channel slope (Sl) were determined for each USGS gage using automated watershed delineation facilitated by ArcHydro 2.0 in ArcGIS 10.0 (Djokic 2008). 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). These DEMs have a grid spacing of three arc-seconds, which is approximately 10 m depending on latitude. Higher-resolution DEMs are available for a number of the watersheds included in this analysis, but it is important to use a consistent resolution, particularly for the determination of main-channel length and channel slope. 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.

Mean soil permeability of the full-depth soil profile was computed for each watershed using the soil permeability map produced for McEnroe et al. (2013), shown in Figure 3-2. This permeability map was generated using the U.S. General Soil Map (STATSGO2) produced by the Natural Resources Conservation Service (NRCS) (NRCS 2012). The STATSGO2 dataset includes a representative hydraulic conductivity for each soil horizon of each soil component. These representative hydraulic conductivities were averaged with respect to depth for each soil component and spatially for each soil map unit (made up of several soil components).

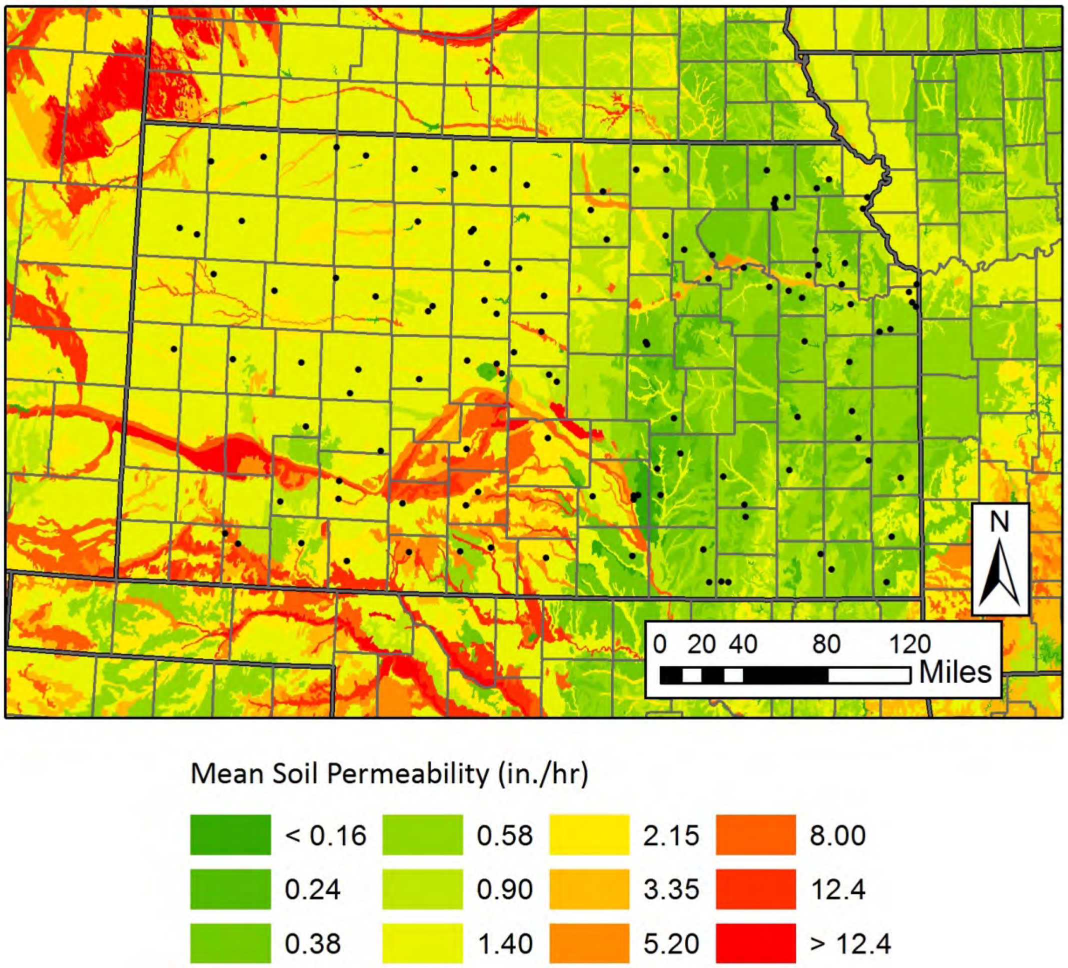


FIGURE 3-2: Mean Soil Permeability (inch/hour) of Full Depth of Soil

The time of concentration, t_c, is the time required for runoff to travel from the most remote point in the watershed to the watershed outlet during a storm event. Time of concentration is an important measure of how quickly runoff reaches the watershed outlet. The t_c

for each watershed was estimated using the KU-KDOT equation for rural watersheds (McEnroe and Zhao, 2000):

$$t_c = 0.176 \left(\frac{L}{\sqrt{Sl}}\right)^{0.66}$$ **Equation 3-1**

in which:

t_c = time of concentration (hr)

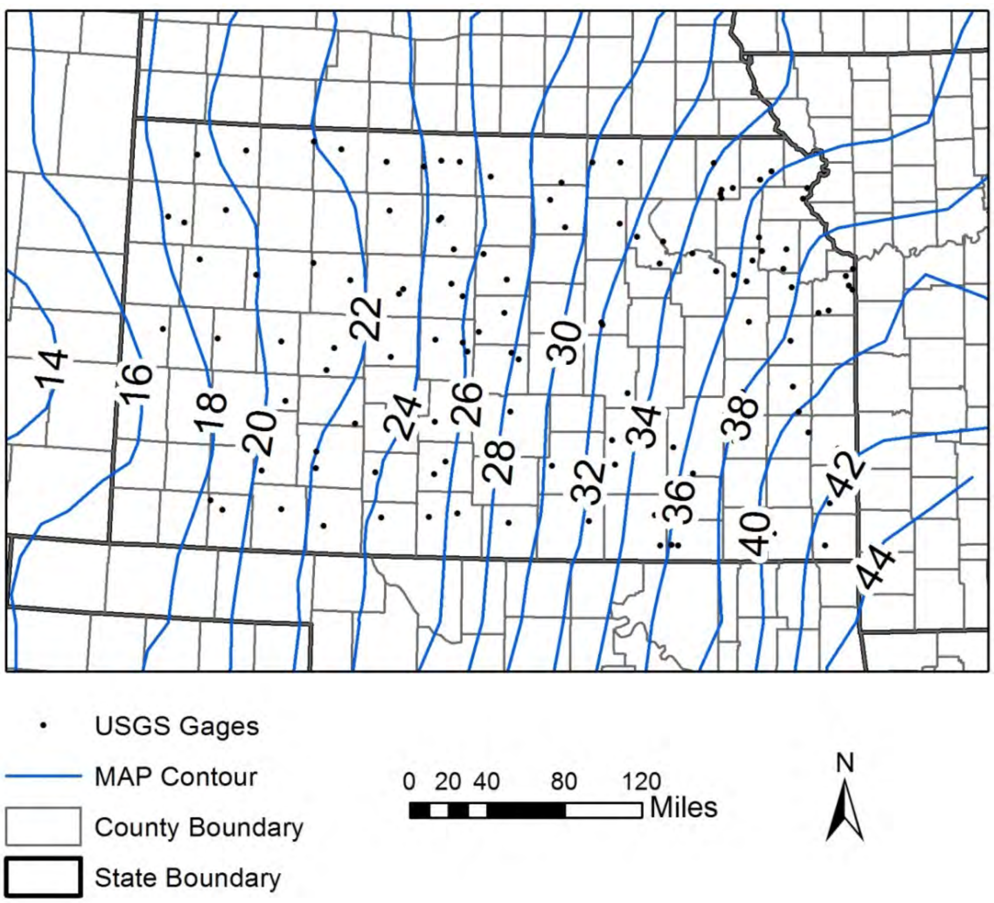
L = length of main channel, extended to the drainage divide (mi)

Sl = average slope of main channel (ft/ft) measured between points 10% and 85% of the distance from the watershed outlet to the watershed boundary.

The KU-KDOT equation was developed from an analysis of rainfall and streamflow records for 20 rural watersheds in Kansas ranging in size from 0.81 to 10.0 mi^2. Although many of the watersheds in this study fall outside the spatial and size range of the basins used to generate Equation 3-1, this equation is still the best available for use in this study. It was important to use one consistent equation for t_c for all of the watersheds in the data set.

The representative rainfall intensity selected for this research was the i_1, or the rainfall intensity for the average recurrence interval (ARI) of one year, selected for a duration equal to the time of concentration (t_c) of the watershed. The i_1 rainfall intensities were extracted from NOAA Atlas 14 Volume 8 (Perica et al. 2013) using the new KDOT county-based rainfall tables described in McEnroe and Young (2013). The 1-year event was selected (instead of the rainfall intensity corresponding to an AEP of 0.84) because the 1-year rainfall is the lowest-frequency rainfall value generated in NOAA Atlas 14. Selection of this characteristic rainfall intensity avoids the need for extrapolation. A rainfall event with ARI = 1 year has an annual exceedance probability of 0.632. It should be noted that the 1-year rainfall is used here as a statistical predictor of the Q_{OHW}, much in the same way that the MAP is used in the USGS regression equations for Kansas (Rasmussen and Perry 2000).

The mean annual precipitation for each watershed was extracted from a digital version of Figure 3-3. This map was generated using the USGS mean annual precipitation map for Kansas from Rasmussen and Perry (2000). The values of MAP in Figure 3-3 are based on rain-gage data collected during the period 1961-1990 (NOAA climate normals are computed over a time span of three decades). More recent climate normals are available (1981-2010); however, we chose to use the MAP values already in use in the KDOT Design Manual for other hydrologic methods to avoid confusion.



Rainfall contours based on Rasmussen and Perry (2000)

FIGURE 3-3: Locations of Selected Stations and Mean Annual Precipitation (inch)

Generalized Least Squares Regression (GLSR) was conducted to develop a regression equation to predict the Q_{OHW} using watershed characteristics. GLS is a sophisticated regression technique that weights individual gage records based on the uncertainty in the flood frequency analysis results (Stedinger and Tasker 1985). GLS also accounts for correlation among nearby stations and the different time spans covered by gages. We used the WREG 1.1 computer program developed and maintained by the USGS (Eng et al. 2009) to conduct GLS regression. Forward stepwise regression was used to determine what predictors were statistically significant for the prediction of the Q_{OHW}.

3.3 Results

Equation 3-2 is the final regional regression equation for the estimation of the Q_{OHW} in rural, unregulated watersheds in Kansas. This equation is intended for use as a supplement to and a reality check on a field-determined Q_{OHW} where reliable indicators of the OHWL can be identified. Where no reliable indicators can be found, Equation 3-2 can be used as a best reasonable estimate of the Q_{OHW}.

$$Q_{OHW} = 10^{-7.28} \cdot MAP^{4.55} \cdot Ai_1{}^{0.814}$$ **Equation 3-2**

in which:

QOHW = peak discharge associated with the ordinary high water event (cfs)

MAP = mean annual rainfall from Figure 3-3 (inch)

A = watershed area (acre)

i^1 = rainfall intensity (inch/hour) from McEnroe and Young (2013) for ARI = 1 year and duration = tc

Figure 3-4 shows a scatter plot of the predicted values of the Q_{OHW} using Equation 3-2 versus the Q_{OHW} derived using flood frequency analysis of the gage record. The model standard error of the estimate for Equation 3-2 is 85.7%, as computed by WREG according to GLS methods.

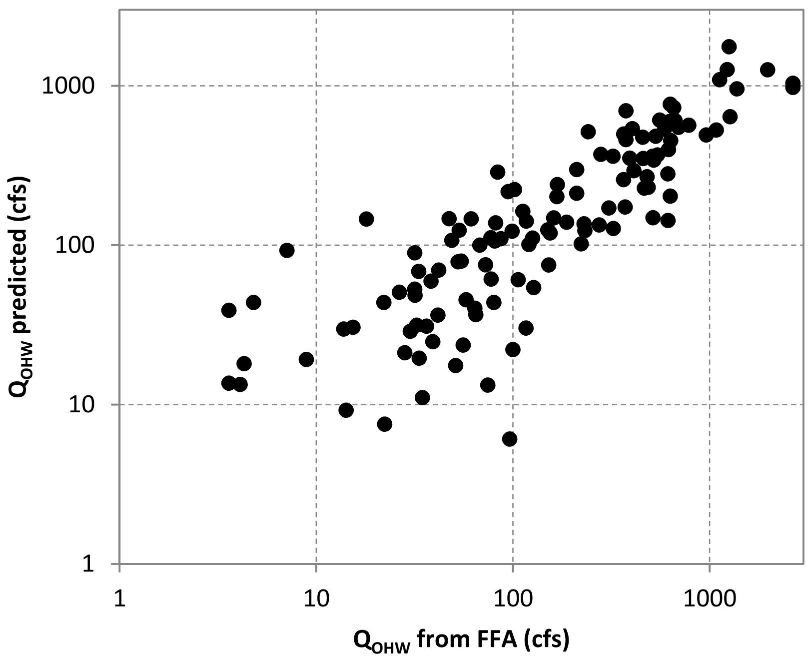


FIGURE 3-4: Q_{OHW} Predicted Using Equation 3-2 Versus Q_{OHW} Estimated using Flood Frequency Analysis

3.4 Conclusions

This chapter presents an equation for the estimation of Q_{OHW} based on watershed characteristics in small (CDA ranging from 0.18 to 30 mi^2 in eastern Kansas and from 0.86 to 100 mi^2 in western Kansas), rural, unregulated streams in Kansas. The equation uses the mean annual precipitation, the drainage area, and the rainfall intensity for ARI = 1 year as predictors. The equation is intended as a supplement to and a reality check for field determination of the Q_{OHW}. If there are no reliable field indicators of the OHWL, Equation 3-2 can be used as a sole estimator of the Q_{OHW}.

3.5 Example

A highway design project will affect the drainage structure for a stream in Jackson County, Kansas. The watershed to the stream is rural and there are no significant flood control structures. ArcGIS is used to delineate the watershed and main channel (extending from the outlet to the drainage divide) for this structure. Using ArcGIS, the design engineer determines the following characteristics:

A = total watershed area = 20.0 mi^2 = 12,800 acres.

L = main channel length, extending from the outlet to the drainage divide = 10 mi.

Sl = slope between points 10% and 85% of the distance from the outlet to the drainage divide = 14.45 ft/mi = 0.00274 ft/ft.

Using Equation 3-1, the design engineer computes the time of concentration as:

$$t_c = 0.176\left(\frac{L}{\sqrt{Sl}}\right)^{0.66} = 0.176\left(\frac{10.0}{\sqrt{0.00274}}\right)^{0.66} = 5.64\ hrs$$

The design engineer then finds the bounding rainfall intensity values from the KDOT rainfall tables based on NOAA Atlas 14 (Perica et al. 2013):

i_1 for 5.5-hr duration = 0.40 inch/hour

i_1 for 5.75-hr duration = 0.39 inch/hour

Interpolating between these values for the 5.64-hr duration yields i_1 = 0.394 inch/hour. Consulting Figure 3-3, the engineer determines the MAP = 35 inches. Using Equation 3-2, the engineer computes the Q_{OHW} as:

$$Q_{OHW} = 10^{-7.28} \cdot 35.0^{4.55} \cdot (12800 \cdot 0.394)^{0.814} = 575\ cfs$$

Chapter 4: Estimating the Q_{OHW} Using HEC-HMS

Chapter 3 presents a regional regression equation for estimating the Q_{OHW} for rural, unregulated streams in Kansas. The equation developed in Chapter 3 is not applicable for streams with a significant degree of regulation or for watersheds that differ significantly from typical rural land cover in Kansas. This chapter presents the development of a method to estimate the Q_{OHW} in Kansas using the USACE's Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS). The end product of this chapter is a calibrated HEC-HMS modeling method that recommends the best combination of storm duration and antecedent moisture condition (AMC) for estimation of the Q_{OHW} in Kansas.

4.1 Dataset

The dataset used in this analysis is the same as described in Chapter 3 with two additional parameters: the lag time (t_{lag}), and Natural Resources Conservation Service (NRCS) runoff curve number (CN) for an average AMC, or the CN_2. Lag time can be computed using the KU-KDOT lag-time equation (McEnroe and Zhao, 2000):

$$t_{lag} = 0.1056\left(\frac{L}{\sqrt{Sl}}\right)^{0.66}$$ **Equation 4-1**

in which:

t_{lag} = watershed lag time (hr)
L = length of main channel, extended to the drainage divide (mi)
Sl = average slope of main channel (ft/ft)

We computed the CN_2 (CN for an average AMC) for each watershed using land cover and soils data in ArcGIS, using an approach similar to that described by McEnroe and Gonzalez (2003). In this study, the NRCS hydrologic soil group was obtained from the U.S. General Soil

Map (STATSGO2) produced by the NRCS (2012). Table 4-1 presents the CN_2 values used for the ArcGIS-based calculations. Figure 4-1 shows a CN_2 map of Kansas.

TABLE 4-1: CN_2 Values Used for GIS-Based Estimates of CN_2

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

4.2 Methodology

The methodology followed for this chapter is similar to the approach used to develop the guidelines for storm duration and AMC in the KDOT Design Manual (KDOT 2011; McEnroe and Gonzalez 2003). Each watershed was simulated in HEC-HMS using the appropriate watershed area and lag time. A design-storm duration of three hours was used for watersheds in western Kansas, and a storm duration of six hours was used for watersheds in eastern Kansas. These durations were selected based on the guidelines in the KDOT Design Manual (KDOT 2011) for an event with T = 1/AEP = 2 years.

4.2.1 Extrapolation of Rainfall Depths

We constructed the design storms in HEC-HMS using the HEC frequency-based storm, which requires input of rainfall depths for durations of 5-min, 15-min, 1-hr, 2-hr, 3-hr, and for eastern Kansas 6-hr. In order to simulate the Q_{OHW}, we extrapolated from the NOAA Atlas 14 precipitation frequency estimates for ARI = 1 and 2 years down to the ARI = 6.5 months (0.545 years). An ARI of 6.5 months is equivalent to an AEP of 0.84 or the 84%-chance event.

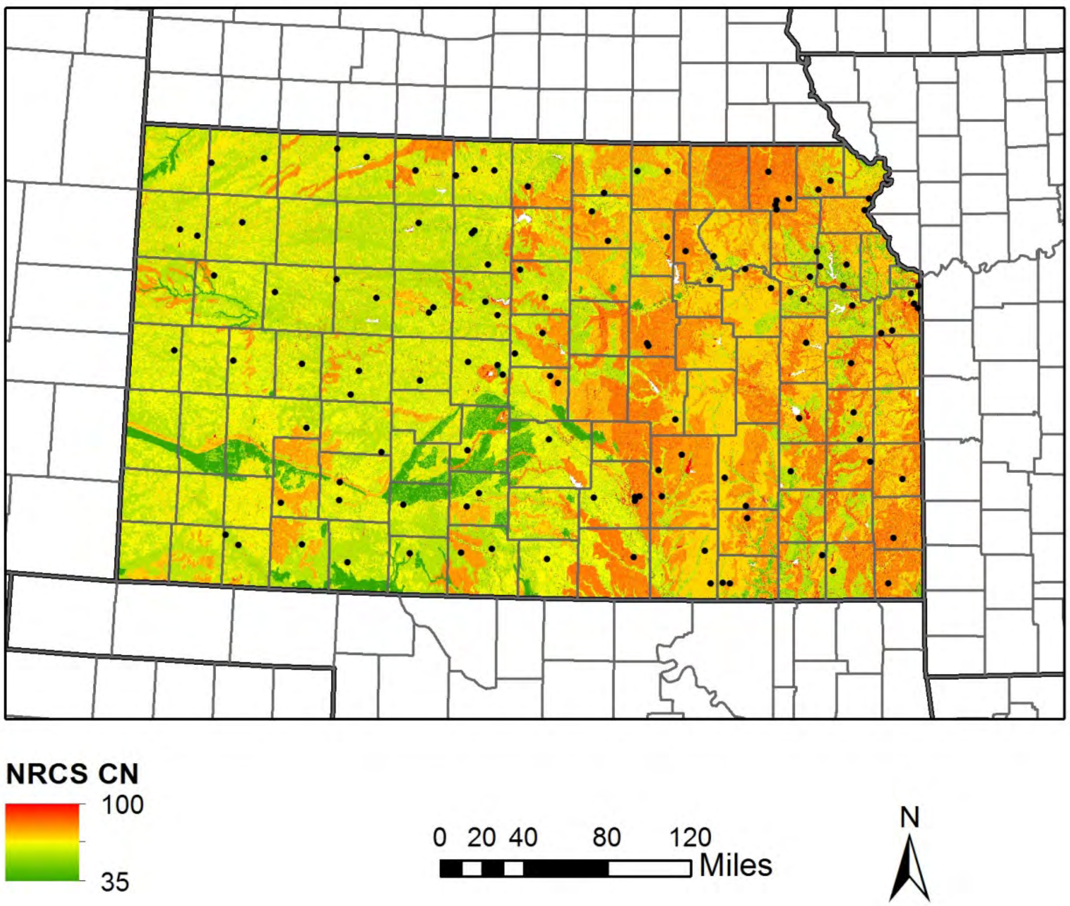


FIGURE 4-1: NRCS Runoff Curve Numbers for AMC 2

To extrapolate the rainfall depths for the 84%-chance event (AEP = 0.84 and ARI = 0.545 years), we fit a Gumbel probability distribution to the 1-yr and 2-yr depths from the KDOT rainfall tables. The resulting equation is shown below; the complete derivation is presented in Appendix B.

$$P_{D,ARI=0.545yr} = 1.874 \cdot P_{D,ARI=1yr} - 0.874 \cdot P_{D,ARI=2yr}$$ **Equation 4-2**

In which:

D	=	rainfall duration of interest
$P_{D,ARI=0.545yr}$	=	rainfall depth for the 84%-chance event (ARI = 0.545 years)
$P_{D,ARI=1yr}$	=	rainfall depth for the ARI = 1 year event, which can be obtained from the 2013 KDOT rainfall tables (McEnroe et al. 2013) which are based on NOAA Atlas 14 Volume 8 (Perica et al. 2013)
$P_{D,ARI=2yr}$	=	rainfall depth for the ARI = 2 years event.

Equation 4-2 can be used to extrapolate the rainfall values necessary for HEC-HMS simulation of the Q_{OHW} event.

4.2.2 Determination of Curve Number and AMC

The 84%-chance event for each watershed was simulated in HEC-HMS using the appropriate design storm, watershed area and lag time as described above. The watershed curve number was adjusted by trial and error until the peak flow simulated by HEC-HMS matched the Q_{OHW} ($Q_{84\%}$) as determined from FFA of the gage record for that location. This calibrated curve number was then compared with the CN_1, CN_2, and CN_3 estimated using the ArcGIS-based CN_2 values, where the CN_1 and CN_3 values are computed using Equations 4-3 and 4-4 (SCS 1986). In this manner, we were able to calculate the AMC for each watershed that generated the best estimate of the Q_{OHW}.

$$CN_1 = \frac{4.2 \cdot CN_2}{10 - 0.058 \cdot CN_2}$$ **Equation 4-3**

$$CN_3 = \frac{23 \cdot CN_2}{10 + 0.13 \cdot CN_2}$$ **Equation 4-4**

4.3 Results

Figure 4-2 presents the distribution of AMC values determined for the 120 watersheds in the study. As can be seen from the histogram, the calibrated AMC values range from 0.8 to 3.3, with a central tendency just below 2.0. Figures 4-3 and 4-4 show the histograms of AMC values for western and eastern Kansas, respectively. AMC values in western Kansas tend to be a little bit higher, on average, than those calibrated in the eastern part of the state. This is in part due to the different storm durations used for the two regions (3-hr storm in western Kansas, 6-hr storm in eastern Kansas).

Table 4-2 summarizes the distribution of AMC values seen in Figures 4-2 through 4-4. Given the wide range of values, and given the possibility for high and low outliers, the median is preferred as a measure of central tendency. Table 4-2 indicates that the median AMC value for western Kansas is 1.9 while the median AMC value for eastern Kansas is 1.6.

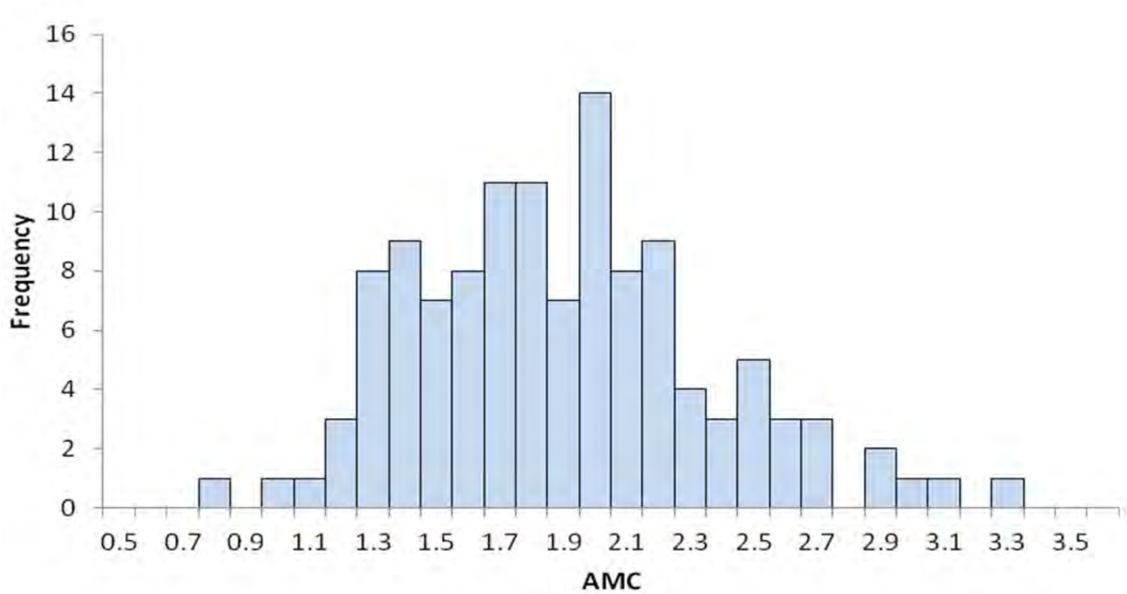


FIGURE 4-2: AMC Value Histogram for all Stations in Kansas

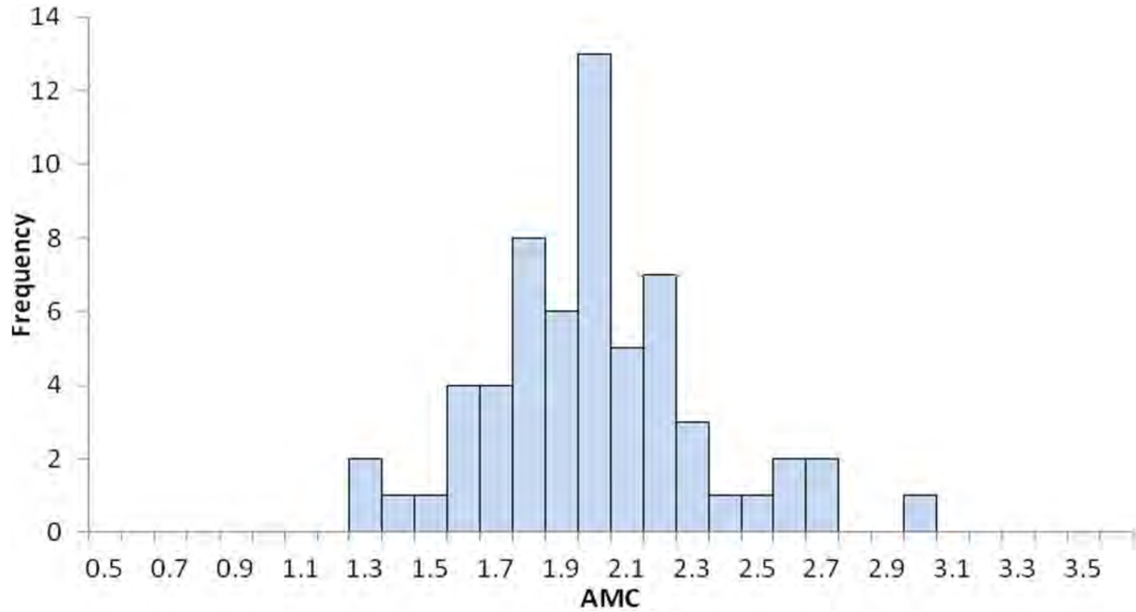


FIGURE 4-3: AMC Value Histogram for Stations in Western Kansas

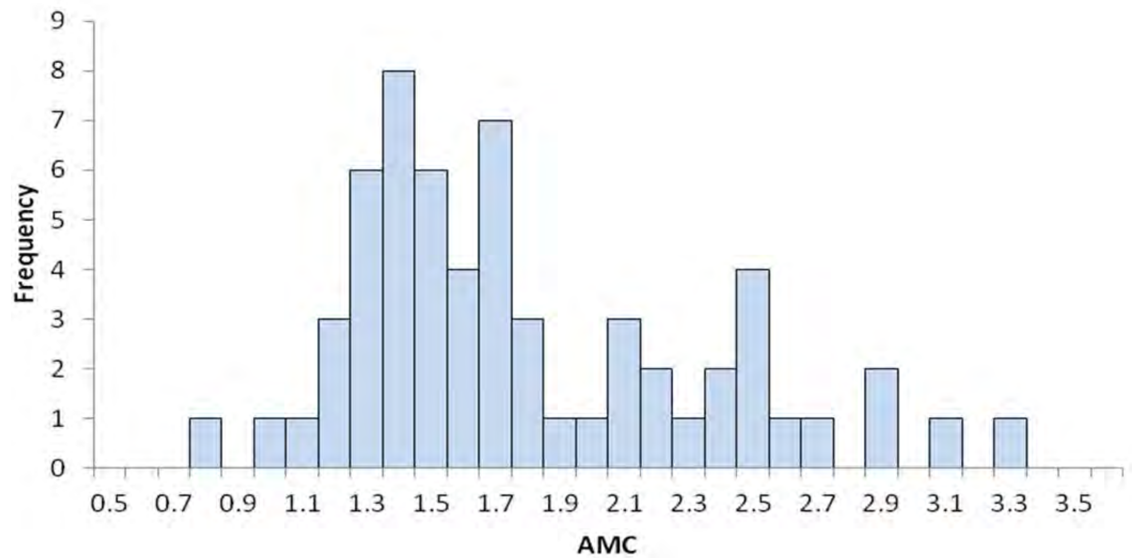


FIGURE 4-4: AMC Value Histogram for Stations in Eastern Kansas

TABLE 4-2: Summary Table of AMC Values for 84%-Chance Event

Region	Average	Minimum	Maximum	Median
All	1.8	0.8	3.3	1.9
West	1.9	1.2	2.9	1.9
East	1.7	0.8	3.3	1.6

4.4 Recommendations

Table 4-3 presents the recommended combination of storm duration and AMC for determination of the Q_{OHW} using HEC-HMS. The HEC-HMS procedure may be preferable to the regression equation presented in Chapter 3 if the streamflow is regulated to a significant degree or the land cover deviates significantly from typical rural Kansas conditions.

TABLE 4-3: Recommended Storm Duration and AMC for Estimation of Q_{OHW} in Kansas

Region	Storm duration (hr)	AMC
West	3	2.0
East	6	1.5

The $CN_{1.5}$ for a watershed is equal to $(CN_1 + CN_2) / 2$. Substituting Equation 4-3 for the CN_1 gives:

$$\mathrm{CN}_{1.5} = \frac{\mathrm{CN}_2 \cdot (7.1 - 0.029\mathrm{CN}_2)}{10 - 0.058 \cdot \mathrm{CN}_2}$$ **Equation 4-5**

4.5 HEC-HMS Procedure for Determining Q_{OHW}

The recommended HEC-HMS procedure for determination of the Q_{OHW} in Kansas is:

1. Determine the watershed area (A, in mi^2). Determine the main channel length from the outlet to the drainage divide (L, in miles) and slope between points 10% and 85% of the way from the outlet to the drainage divide (Sl, in ft/ft). We recommend using ArcHydro in conjunction with ArcGIS to delineate the watershed area and channel characteristics.

If possible, a 3 arc-second DEM should be used to ensure methodological consistency with this report.

2. Compute the basin lag time using Equation 4-1:

$$t_{lag} = 0.1056\left(\frac{L}{\sqrt{Sl}}\right)^{0.66} \qquad \textbf{Equation 4-1}$$

3. Estimate the watershed CN_2 following guidelines outlined in the KDOT Design Manual (KDOT 2011).
4. If the watershed is in eastern Kansas (as defined by Figure 3-1), compute the $CN_{1.5}$ using Equation 4-5, repeated below.

$$CN_{1.5} = \frac{CN_2 \cdot (7.1 - 0.029CN_2)}{10 - 0.058 \cdot CN_2} \qquad \textbf{Equation 4-5}$$

5. Obtain the rainfall depths for durations of 5 minutes, 15 minutes, 1 hour, 2 hours, 3 hours and (for eastern Kansas only) 6 hours for ARI = 1 year and ARI = 2 years using the revised KDOT rainfall tables based on NOAA Atlas 14 Volume 8 (McEnroe and Young 2013).
6. Extrapolate the rainfall depths for the necessary durations for ARI = 0.545 years (AEP = 0.84) using Equation B-8:

$$P_{D,ARI=0.545yr} = 1.874 \cdot P_{D,ARI=1yr} - 0.874 \cdot P_{D,ARI=2yr} \qquad \textbf{Equation B-8}$$

7. Model the basin in HEC-HMS using the area, lag time, and CN. Use a frequency-based storm with the duration of three hours for western Kansas or six hours for eastern Kansas.

4.6 Example

A highway design project will affect the drainage structure for a stream in Jackson County, Kansas. The watershed to the stream is rural and there are no significant flood control structures.

1. ArcGIS is used to delineate the watershed and main channel (extending from the outlet to the drainage divide) for this structure. Using ArcGIS, the design engineer determines the following characteristics:

   A = total watershed area = 20.0 mi^2 = 12,800 acres.

L = main channel length, extending from the outlet to the drainage divide = 10 mi.

Sl = slope between points 10% and 85% of the distance from the outlet to the drainage divide = 14.45 ft/mi = 0.00274 ft/ft.

2. Using Equation (4-1), the design engineer computes the lag time as:

$$t_{lag} = 0.1056\left(\frac{L}{\sqrt{Sl}}\right)^{0.66} = 0.1056\left(\frac{10.0}{\sqrt{0.00274}}\right)^{0.66} = 3.38\ hrs$$

3. Using ArcGIS, the design engineer estimates the CN_2 for the watershed as 82.
4. Since the watershed is in eastern Kansas, the $CN_{1.5}$ is computed as:

$$CN_{1.5} = \frac{82 \cdot (7.1 - 0.029 \cdot 82)}{10 - 0.058 \cdot 82} = 73.8 \qquad \textbf{Equation 4-5}$$

5. Obtain the rainfall depths for ARI = 1 year and 2 years from the updated KDOT rainfall tables based on Perica et al. (2013).
6. Extrapolate using Equation 4-7:

DURATION (H:M)	From 2013 KDOT Rainfall Tables based on NOAA Atlas		Extrapolated using Eq. 4-7
	ARI = 1 yr	ARI= 2 yr	ARI = 0.545 yr
0:05	0.41	0.48	0.35
0:15	0.73	0.85	0.63
1:00	1.35	1.59	1.14
2:00	1.67	1.98	1.40
3:00	1.88	2.23	1.57
6:00	2.24	2.66	1.87

7. Set up a HEC-HMS model for the watershed using:

<u>Basin Model Settings:</u>
A = 20 mi
Loss Method = SCS Curve Number
Transform Method = SCS Unit Hydrograph
CN = 73.8
Impervious (%) = 0.0 (rural watershed)
Lag time = 3.38 hrs = 202.8 min

Meteorologic Model Settings:
Frequency Storm
Probability: 50 Percent (this setting will not affect the results)
Input Type: Partial Duration
Output Type: Partial Duration
Intensity Duration: 5 Minutes
Storm Duration: 6 Hours
Intensity Position: 50 Percent
Storm Area: (leave blank, will be set to watershed area)

Control Specification Settings:
Start Date: 01Jan2000 (arbitrary date)
Start Time: 00:00 (arbitrary time)
End Date: 02Jan2000 (run the model for at least 6 hours, running for 24 hours here)
End Time: 00:00
Time Interval: 1 Minute

For this watershed, HEC-HMS generates an estimated Q_{OHW} = 630 cfs.

Chapter 5: Conclusions and Summary of Recommendations

This report provides two methods for the hydrologic estimation of the discharge responsible for the ordinary high water level in Kansas. The regression-based approach developed in Chapter 3 uses watershed area, a characteristic rainfall intensity, and the mean annual precipitation to estimate the Q_{OHW}. Chapter 4 presents a HEC-HMS flood hydrograph simulation method for estimating the Q_{OHW}.

Both methods presented in this report rely on the functional equivalence between the bankfull stage, as defined by Rosgen (1996) and Harrelson et al. (1994), and the OHW level as defined by USACE (2005). Chapter 2 demonstrates that the reliable indicators of OHW map directly to the physical characteristics that define the bankfull stage in self-formed, natural channels. Research by McEnroe et al. (2009) indicates that the average recurrence interval (ARI) for the bankfull flow in Kansas is 0.545 years. As such, the frequency of the OHW flow in Kansas streams can be estimated as an event with ARI = 0.545 years or 6.5 months. The 6.5-month event has an annual exceedance probability (AEP) of 0.84 and may be referred to as the 84%-chance event.

This frequency-based definition of the Q_{OHW} is supported by USACE (2005) which states that the OHW level should be an indication of 'regular or frequent' high-water levels. The 6.5-month event will occur about twice per year, and will be equaled or exceeded in approximately 84% of years. The return period (defined here as T = 1/AEP) for this event is approximately 1.2 years.

USACE (2005) states a clear preference for the use of on-site, physical indicators of the OHW. Where possible, two or more of the characteristics in Table 2-2 should be used to identify the OHW in Kansas streams. The hydrologic methods presented in Chapters 3 and 4 can be used as a check on field estimates, or in lieu of field determination where physical indicators are absent, misleading, or inconclusive.

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Appendix A: USGS-Gaged Watersheds Used in this Report

TABLE A-1: Station List for Selected Gages in Western Kansas

Station Number	Station Name	County	Start Date	End Date	Years of Record
06844700	SF SAPPA C NR BREWSTER, KS	Sherman	6/22/1968	6/28/1989	22
06844800	SF SAPPA C TR NR GOODLAND, KS	Sherman	5/16/1957	6/28/1989	33
06845100	LONG BRANCH DRAW NR NORCATUR, KS	Norton	6/15/1957	6/21/2010	53
06845900	LITTLE BEAVER C TR NR MCDONALD, KS	Rawlins	7/20/1957	6/7/1966	10
06846200	BEAVER C TR NR LUDELL, KS	Rawlins	6/27/1957	6/11/1905	33
06847600	PRAIRIE DOG C TR AT COLBY, KS	Thomas	7/13/1957	7/8/2012	56
06848200	PRAIRIE DOG C TR NR NORTON, KS	Norton	6/15/1957	9/10/1991	35
06855900	WOLF C NR CONCORDIA, KS	Cloud	6/26/1963	7/26/1981	19
06856100	WEST C NR TALMO, KS	Republic	6/1941	6/24/1989	34
06858700	NF SMOKY HILL R TR NR WINONA, KS	Logan	6/30/1957	8/22/1977	21
06860300	SB HACKBERRY C NR ORION, KS	Gove	6/16/1957	5/23/1905	12
06863400	BIG C TR NR OGALLAH, KS	Trego	6/16/1957	7/4/1905	56
06863700	BIG C TR NR HAYS, KS	Ellis	6/30/1957	7/4/1905	54
06863900	NF BIG C NR VICTORIA, KS	Ellis	7/15/1963	4/14/1987	25
06864300	SMOKY HILL R TR AT DORRANCE, KS	Russell	6/30/1957	7/4/1905	56
06864700	SPRING C NR KANOPOLIS, KS	Ellsworth	6/30/1957	9/8/1989	33
06866800	SALINE R TR AT COLLYER, KS	Trego	6/16/1957	6/27/1989	33
06867800	CEDAR C TR NR BUNKER HILL, KS	Russell	5/16/1957	8/25/1977	21
06868300	COON C TR NR LURAY, KS	Osborne	6/26/1957	4/14/2012	56
06868700	NB SPILLMAN C NR ASH GROVE, KS	Lincoln	3/11/1963	8/23/1977	15
06868900	BULLFOOT C TR NR LINCOLN, KS	Lincoln	7/1/1957	7/15/1989	33
06871900	DEER C NR PHILLIPSBURG, KS	Phillips	7/28/1967	7/2/1981	15
06872100	M CEDAR C AT KENSINGTON, KS	Smith	4/29/1905	8/16/1977	22
06872300	M BEAVER C NR SMITH CENTER, KS	Smith	6/7/1961	4/18/1970	10
06872600	OAK C AT BELLAIRE, KS	Smith	6/16/1957	8/19/1989	33
06873300	ASH C TR NR STOCKTON, KS	Rooks	7/10/1957	7/4/1905	55
06873700	KILL C NR BLOOMINGTON, KS	Osborne	8/17/1964	9/25/1981	18
06873800	KILL C TR NR BLOOMINGTON, KS	Osborne	6/17/1957	8/23/1977	21
06874500	E LIMESTONE C NR IONIA, KS	Jewell	9/3/1934	7/1/1989	38

TABLE A-1: Station List for Selected Gages in Western Kansas (Cont.)

Station Number	Station Name	County	Start Date	End Date	Years of Record
06876200	M PIPE C NR MILTONVALE, KS	Cloud	5/16/1957	6/17/1977	21
07138600	WHITE WOMAN C TR NR SELKIRK, KS	Greeley	6/27/1957	7/2/1905	39
07138800	LION C TR NR MODOC, KS	Scott	6/27/1957	8/7/1977	21
07139700	ARKANSAS R TR NR DODGE CITY, KS	Ford	7/24/1957	7/4/1905	54
07139800	MULBERRY C NR DODGE CITY, KS	Ford	10/16/1968	4/25/1990	22
07140300	WHITEWOMAN C NR BELLEFONT, KS	Hodgeman	7/21/1957	6/24/1989	33
07140600	PAWNEE R TR NR KALVESTA, KS	Finney	6/17/1957	6/5/1989	33
07140700	GUZZLERS GULCH NR NESS CITY, KS	Ness	7/3/1962	6/20/1980	19
07141400	SF WALNUT CR TR NR DIGHTON, KS	Lane	9/11/1957	8/5/1977	21
07141600	LONG BRANCH C NR NESS CITY, KS	Ness	9/11/1957	6/11/1905	33
07141800	OTTER C NR RUSH CENTER, KS	Rush	10/30/1956	6/11/1905	33
07142100	RATTLESNAKE C TR NR MULLINVILLE, KS	Kiowa	6/27/1957	8/13/1989	33
07142500	SPRING C NR DILLWYN, KS	Stafford	6/26/1957	5/21/1977	21
07142700	SALT C NR PARTRIDGE, KS	Reno	5/16/1957	8/15/1989	33
07142860	COW C NR CLAFLIN, KS	Barton	6/29/1967	4/12/1988	22
07142900	BLOOD C NR BOYD, KS	Barton	5/29/1957	9/5/1989	33
07143100	L CHEYENNE C TR NR CLAFLIN, KS	Barton	5/28/1957	7/4/1905	56
07143200	PLUM C NR HOLYROOD, KS	Ellsworth	5/28/1957	8/28/1977	21
07143500	L ARKANSAS R NR GENESEO, KS	Rice	6/27/1957	5/21/1977	21
07143600	L ARKANSAS R NR LITTLE RIVER, KS	Rice	9/24/1960	10/10/1985	26
07144850	SF SF NINNESCAH R NR PRATT, KS	Pratt	10/31/1961	10/29/1979	19
07144900	SF NINNESCAH R TR NR PRATT, KS	Pratt	6/26/1957	5/18/1989	33
07145300	CLEAR C NR GARDEN PLAIN, KS	Sedgwick	5/16/1957	9/9/1989	33
07148700	DOG C NR DEERHEAD, KS	Barber	5/16/1957	5/23/1977	21
07148800	MEDICINE LODGE R TR NR MEDICINE LODGE, KS	Barber	6/27/1957	5/23/1977	21
07151600	RUSH C NR HARPER, KS	Harper	5/16/1957	9/9/1989	33
07156600	CIMARRON R TR NR MOSCOW, KS	Seward	9/11/1957	5/18/1989	33
07156700	CIMARRON R TR NR SATANTA, KS	Seward	9/11/1957	6/12/2010	53
07157100	CROOKED C NR COPELAND, KS	Gray	6/23/1957	6/23/1989	33
07157400	CROOKED C TR AT MEADE, KS	Meade	5/16/1957	6/23/1989	33
07157700	KEIGER C NR ASHLAND, KS	Clark	4/16/1957	8/13/1989	32
07157900	CAVALRY C AT COLDWATER, KS	Comanche	5/16/1957	7/17/1988	28

TABLE A-2: Station List for Selected Gages in Eastern Kansas

Station Number	Station Name	County	Start Date	End Date	Years of Record
06813700	TENNESSEE C TR NR SENECA, KS	Nemaha	6/29/1957	9/9/1989	33
06815700	BUTTERMILK C NR WILLIS, KS	Brown	6/30/1957	9/22/2010	52
06818200	DONIPHAN C AT DONIPHAN, KS	Doniphan	6/23/1960	6/16/1970	11
06818260	WHITE CLAY C AT ATCHISON, KS	Atchison	9/7/1972	7/4/1905	40
06856800	MOLL C NR GREEN, KS	Clay	6/26/1957	7/26/1990	34
06877200	W TURKEY C NR ELMO, KS	Dickinson	5/16/1957	5/30/1977	21
06877400	TURKEY C TR NR ELMO, KS	Dickinson	6/27/1957	8/28/1977	21
06879650	KINGS C NR MANHATTAN, KS	Riley	3/29/1980	3/22/2012	33
06879700	WILDCAT C AT RILEY, KS	Riley	6/16/1957	8/23/1977	21
06884100	MULBERRY C TR NR HADDAM, KS	Washington	8/15/1957	9/9/1989	32
06884300	MILL C TR NR WASHINGTON, KS	Washington	8/15/1957	7/4/1905	55
06887200	CEDAR C NR MANHATTAN, KS	Pottawatomie	6/26/1957	3/22/2012	56
06887600	KANSAS R TR NR WAMEGO, KS	Wabaunsee	1951-07	6/16/1990	35
06888600	DRY C NR MAPLE HILL, KS	Wabaunsee	1939	6/19/1977	22
06888900	BLACKSMITH C TR NR VALENCIA, KS	Shawnee	7/10/1957	9/8/1989	33
06889100	SOLDIER C NR GOFF, KS	Nemaha	9/20/1965	5/27/1987	23
06889120	SOLDIER C NR BANCROFT, KS	Nemaha	9/21/1965	4/2/1988	24
06889140	SOLDIER C NR SOLDIER, KS	Jackson	9/20/1965	9/20/1998	34
06889550	INDIAN C NR TOPEKA, KS	Shawnee	6/11/1970	12/10/2011	43
06889600	SB SHUNGANUNGA C NR PAULINE, KS	Shawnee	7/10/1957	5/12/2010	26
06890000	L DELAWARE R NR HORTON, KS	Brown	1951-07	4/9/1978	12
06890300	SPRING C NR WETMORE, KS	Nemaha	6/29/1957	9/12/1977	21
06890560	ROCK C 6 MILES N OF MERIDEN, KS	Jefferson	6/22/1964	9/12/1977	14
06890600	ROCK C NR MERIDEN, KS	Jefferson	6/8/1957	6/11/1970	14
06890700	SLOUGH C TR NR OSKALOOSA, KS	Jefferson	7/10/1957	9/12/1977	21
06891050	STONE HOUSE CR AT WILLIAMSTOWN, KS	Jefferson	5/26/1963	4/1/1988	26
06891650	NAISMITH C AT LAWRENCE, KS	Douglas	10/11/1973	2/28/2012	25
06892800	TURKEY C AT MERRIAM, KS	Johnson	10/11/1973	5/6/2012	20
06892940	TURKEY C AT KANSAS CITY, KS	Wyandotte	6/9/1974	4/13/1987	14

TABLE A-2: Station List for Selected Gages in Eastern Kansas (Cont.)

Station Number	Station Name	County	Start Date	End Date	Years of Record
06893300	INDIAN C AT OVERLAND PARK, KS	Johnson	5/26/1964	5/6/2012	49
06893350	TOMAHAWK C NR OVERLAND PARK, KS	Johnson	9/22/1970	5/6/2012	15
06912300	DRAGOON C TR NR LYNDON, KS	Osage	7/10/1957	5/16/1990	34
06913600	ROCK C NR OTTAWA, KS	Franklin	7/10/1957	6/18/1977	21
06914250	SF POTTAWATOMIE C TR NR GARNETT, KS	Anderson	3/4/1963	9/15/2010	46
06914950	BIG BULL C NR EDGERTON, KS	Johnson	6/8/1994	3/20/2012	19
06914990	L BULL C NR SPRING HILL, KS	Johnson	6/8/1994	5/6/2012	19
06916700	MIDDLE C NR KINCAID, KS	Anderson	5/16/1957	5/21/1990	34
06917100	MARMATON R TR NR BRONSON, KS	Allen	5/16/1957	3/15/1990	34
06917400	MARMATON R TR NR FORT SCOTT, KS	Bourbon	6/9/1957	3/20/2012	56
07144320	GYPSUM C AT GILBERT ST WICHITA, KS	Sedgwick	6/4/1964	5/19/1978	15
07144330	DRY C AT LINCOLN ST WICHITA, KS	Sedgwick	6/4/1964	7/4/1905	23
07145800	ANTELOPE C TR NR DALTON, KS	Sumner	6/12/1957	10/30/1989	34
07146700	WB WALNUT R TR NR DEGRAFF, KS	Butler	5/16/1957	5/21/1977	21
07147020	WHITEWATER R TR NR TOWANDA, KS	Butler	7/12/1963	6/9/2010	47
07147200	DRY CR TR NR AUGUSTA, KS	Butler	5/16/1957	4/13/1977	21
07147990	CEDAR C TR NR CAMBRIDGE, KS	Cowley	5/5/1961	5/1/2012	52
07166200	SANDY C NR YATES CENTER, KS	Woodson	5/16/1957	3/20/2012	56
07166700	BURNT C AT REECE, KS	Woodson	5/16/1957	5/29/1969	13
07169200	SALT C NR SEVERY, KS	Greenwood	5/16/1957	6/22/1977	21
07169700	SNAKE C NR HOWARD, KS	Elk	5/16/1957	6/22/1977	21
07170600	CHERRY C NR CHERRYVALE, KS	Montgomery	5/16/1957	6/21/1977	21
07170800	MUD C NR MOUND VALLEY, KS	Labette	5/16/1957	6/15/1990	34
07171700	SPRING BRANCH NR CEDAR VALE, KS	Chautauqua	5/16/1957	4/27/1994	38
07171800	CEDAR C TR NR HOOSER, KS	Cowley	5/16/1957	10/30/1989	34
07171900	GRANT C NR WAUNETA, KS	Chautauqua	5/16/1957	6/22/1977	21
07180300	SPRING C TR NR FLORENCE, KS	Marion	5/16/1957	6/14/1990	34
07182520	ROCK C AT BURLINGTON, KS	Coffey	4/30/1957	6/19/1977	21
07183800	LIMESTONE C NR BEULAH, KS	Crawford	6/9/1957	6/11/1989	33
07184600	FLY C NR FAULKNER, KS	Cherokee	5/16/1957	6/22/1977	21

TABLE A-3: Watershed Characteristics for Selected Gages in Western Kansas

Station Number	A (mi^2)	L (mi)	Sl (ft/mi)	SP (in./hr)	t_c (hr)	i_1 (in./hr)	$A \cdot i_1$ (ac·in/hr)	MAP (in.)
06844700	85.65	33.65	11.17	1.29	13.65	0.13	7126.1	18.22
06844800	21.12	13.24	13.42	1.29	6.94	0.22	2989.7	17.98
06845100	31.97	16.45	12.73	1.30	8.15	0.22	4439.7	21.91
06845900	8.17	5.91	37.22	1.28	2.91	0.45	2357.5	19.42
06846200	10.68	7.33	33.87	1.29	3.46	0.39	2686.9	20.64
06847600	8.09	6.91	18.12	1.29	4.09	0.34	1773.3	19.61
06848200	1.07	2.18	53.27	1.30	1.34	0.90	615.1	22.28
06855900	56.53	17.99	9.93	1.21	9.39	0.23	8403.0	28.65
06856100	39.98	30.44	8.68	1.23	13.88	0.17	4349.8	28.86
06858700	0.94	1.74	67.70	1.29	1.06	1.00	602.4	18.84
06860300	59.49	37.52	10.17	1.28	15.13	0.13	4901.7	19.61
06863400	4.90	7.78	18.71	1.30	4.38	0.36	1127.8	21.68
06863700	6.06	8.88	17.75	1.22	4.86	0.35	1361.2	23.09
06863900	52.98	27.95	8.77	1.30	13.08	0.16	5398.6	22.99
06864300	5.51	5.01	25.87	1.31	2.94	0.58	2034.6	25.91
06864700	9.70	9.00	19.53	1.31	4.75	0.40	2481.3	27.43
06866800	3.54	3.82	31.60	1.30	2.30	0.60	1367.6	21.04
06867800	1.09	1.72	149.51	1.28	0.81	1.48	1033.9	25.35
06868300	6.54	5.16	43.97	1.24	2.52	0.63	2617.1	25.19
06868700	27.03	16.17	15.17	1.14	7.61	0.27	4633.8	25.98
06868900	2.89	5.17	30.65	1.30	2.84	0.59	1089.5	27.27
06871900	67.64	22.65	15.29	1.36	9.48	0.20	8678.0	22.82
06872100	59.79	29.62	9.76	1.30	13.12	0.16	6077.5	23.97
06872300	72.84	26.92	11.82	1.31	11.56	0.18	8333.4	24.59
06872600	5.38	6.35	23.73	1.30	3.54	0.46	1573.0	25.30
06873300	0.86	1.94	53.40	1.30	1.24	1.01	554.7	22.83
06873700	51.64	20.17	14.76	1.30	8.88	0.22	7350.8	24.22
06873800	1.43	2.89	41.64	1.27	1.75	0.82	751.2	24.41
06874500	26.64	17.81	12.49	1.26	8.64	0.24	4043.3	26.54

TABLE A-3: Watershed Characteristics for Selected Gages in Western Kansas (Cont.)

Station Number	A (mi^2)	L (mi)	Sl (ft/mi)	SP (in./hr)	t_c (hr)	i_1 (in./hr)	$A \cdot i_1$ (ac·in/hr)	MAP (in.)
06876200	9.71	9.48	21.20	1.00	4.79	0.39	2414.3	29.25
07138600	26.33	18.64	15.06	1.29	8.37	0.18	3075.5	16.74
07138800	8.21	10.67	10.22	1.24	6.58	0.26	1348.5	18.61
07139700	9.34	9.36	14.18	1.61	5.42	0.30	1811.7	22.06
07139800	77.48	27.63	9.29	1.34	12.74	0.15	7569.3	21.80
07140300	18.39	12.64	11.54	1.25	7.08	0.24	2806.6	22.59
07140600	26.81	14.22	8.38	0.74	8.50	0.20	3431.7	20.48
07140700	57.49	32.92	10.56	1.30	13.70	0.14	5259.8	21.20
07141400	1.43	3.30	16.21	1.27	2.61	0.54	498.0	20.44
07141600	29.59	23.33	11.08	1.30	10.74	0.18	3316.0	21.43
07141800	17.41	13.06	14.31	1.29	6.73	0.27	3015.9	22.85
07142100	10.00	10.42	10.98	1.25	6.33	0.29	1834.9	23.82
07142500	48.53	22.47	6.97	5.48	12.22	0.18	5523.7	24.60
07142700	93.95	29.32	6.58	4.28	14.84	0.16	9716.8	27.78
07142860	43.26	16.90	7.12	1.35	10.05	0.21	5786.0	25.90
07142900	62.62	19.49	10.16	1.34	9.82	0.21	8561.3	24.41
07143100	1.53	3.24	20.54	1.34	2.38	0.67	654.8	26.14
07143200	19.13	11.86	10.95	1.33	6.90	0.29	3599.1	26.53
07143500	24.51	10.59	13.06	1.22	6.04	0.33	5148.8	27.76
07143600	71.96	19.29	8.76	1.21	10.24	0.22	9908.4	28.02
07144850	21.59	13.31	10.70	2.35	7.51	0.27	3727.8	25.27
07144900	1.59	2.65	23.74	2.82	1.99	0.74	758.1	25.73
07145300	5.24	5.49	18.31	1.29	3.51	0.55	1842.4	30.44
07148700	5.03	3.95	65.17	1.87	1.85	0.80	2584.0	25.49
07148800	2.15	3.35	35.85	1.86	2.03	0.75	1033.4	26.39
07151600	11.89	11.39	20.27	1.77	5.48	0.38	2896.7	28.73
07156600	19.68	11.56	23.56	2.30	5.27	0.28	3515.9	18.26
07156700	3.03	4.82	32.80	3.44	2.65	0.48	937.1	19.08
07157100	54.42	18.94	12.83	1.03	8.92	0.20	7019.0	20.05
07157400	8.46	9.69	31.73	1.07	4.25	0.34	1840.3	21.02
07157700	34.35	21.522	26.62	1.80	7.63	0.23	4999.2	22.43
07157900	41.72	17.958	11.4	1.92	8.96	0.22	5897.1	24.24

TABLE A-4: Watershed Characteristics for Selected Gages in Eastern Kansas

Station Number	A (mi^2)	L (mi)	Sl (ft/mi)	SP (in./hr)	t_c (hr)	i_1 (in./hr)	$A \cdot i_1$ (ac·in/hr)	MAP (in.)
06813700	0.90	2.00	62.59	0.46	1.20	1.21	693.1	34.01
06815700	3.70	3.73	23.68	0.60	2.49	0.73	1732.8	35.87
06818200	4.13	3.93	41.99	1.16	2.14	0.80	2119.9	36.71
06818260	12.97	7.43	35.00	1.07	3.46	0.58	4773.6	36.89
06856800	4.49	5.15	21.04	0.73	3.21	0.58	1652.6	31.42
06877200	26.18	14.71	10.66	0.49	8.03	0.29	4851.1	31.97
06877400	2.49	4.29	31.41	0.44	2.49	0.70	1118.3	31.96
06879650	4.38	3.59	82.88	0.82	1.61	0.98	2750.5	33.52
06879700	13.77	10.64	11.70	0.62	6.28	0.35	3072.4	32.08
06884100	1.55	2.25	48.25	1.21	1.41	1.03	1021.7	30.16
06884300	2.92	3.33	42.38	0.99	1.91	0.82	1535.2	30.96
06887200	14.93	8.72	39.07	0.74	3.70	0.53	5022.7	33.37
06887600	0.82	1.86	95.49	0.61	0.99	1.38	724.1	34.44
06888600	15.88	8.86	20.62	0.66	4.62	0.46	4679.3	35.36
06888900	0.76	2.05	59.69	0.56	1.24	1.18	575.2	35.96
06889100	2.05	3.38	26.28	0.47	2.26	0.77	1005.8	34.69
06889120	10.58	6.77	17.95	0.47	4.05	0.50	3359.8	34.74
06889140	17.00	9.96	14.23	0.46	5.64	0.39	4290.4	34.82
06889550	9.81	7.92	22.03	0.58	4.20	0.49	3051.5	36.36
06889600	4.11	4.55	27.43	0.55	2.71	0.67	1777.0	36.39
06890000	19.14	11.44	11.99	0.51	6.54	0.35	4265.4	35.56
06890300	20.86	10.52	20.12	0.46	5.22	0.40	5374.8	34.88
06890560	1.92	2.99	41.62	0.58	1.79	0.91	1113.7	36.44
06890600	22.09	13.50	12.04	0.60	7.29	0.32	4502.0	36.59
06890700	0.85	1.79	49.00	0.52	1.21	1.19	648.6	37.43
06891050	13.22	7.91	34.49	0.83	3.62	0.55	4618.3	37.49
06891650	1.43	2.25	65.84	0.76	1.28	1.14	1043.6	37.88
06892800	6.81	4.52	27.67	1.24	2.69	0.69	2993.1	38.93
06892940	22.22	11.27	22.35	1.21	5.28	0.41	5802.7	38.88

TABLE A-4: Watershed Characteristics for Selected Gages in Eastern Kansas (Cont.)

Station Number	A (mi^2)	L (mi)	Sl (ft/mi)	SP (in./hr)	t_c (hr)	i_1 (in./hr)	$A \cdot i_1$ (ac·in/hr)	MAP (in.)
06893300	26.34	15.26	12.69	0.92	7.76	0.31	5305.3	39.00
06893350	21.67	12.34	15.26	0.86	6.35	0.37	5076.4	39.12
06912300	3.73	3.07	37.92	0.71	1.88	0.90	2154.7	36.81
06913600	11.19	9.49	10.02	0.70	6.13	0.37	2682.7	38.27
06914250	0.40	1.01	112.18	0.85	0.63	1.91	486.3	39.39
06914950	29.02	10.08	15.53	0.87	5.52	0.41	7596.8	38.66
06914990	8.00	6.38	15.93	0.92	4.05	0.52	2642.0	38.92
06916700	2.16	2.79	40.43	1.09	1.73	1.01	1391.4	40.05
06917100	0.90	1.89	32.76	1.12	1.43	1.15	659.9	40.67
06917400	2.83	3.69	34.69	1.01	2.18	0.85	1531.2	41.57
07144320	8.80	6.95	13.56	0.31	4.52	0.45	2531.1	32.40
07144330	3.33	4.03	21.73	1.15	2.70	0.67	1429.7	32.31
07145800	0.41	1.47	48.41	0.58	1.07	1.33	353.6	32.26
07146700	10.18	9.96	13.47	0.63	5.74	0.39	2545.1	33.79
07147020	0.18	1.02	64.51	0.44	0.76	1.70	198.5	33.00
07147200	0.89	1.42	47.90	0.44	1.04	1.38	787.3	33.31
07147990	2.52	3.66	53.45	0.80	1.88	0.92	1485.9	35.41
07166200	6.93	5.62	22.19	0.78	3.34	0.63	2775.2	38.36
07166700	9.13	6.57	36.07	0.70	3.15	0.66	3831.3	35.38
07169200	7.65	4.68	33.61	0.64	2.58	0.73	3573.7	36.55
07169700	1.80	2.26	49.46	0.55	1.41	1.14	1309.1	36.79
07170600	15.13	7.39	16.98	0.89	4.37	0.52	4991.5	40.39
07170800	4.42	3.78	29.72	1.17	2.34	0.83	2347.9	40.61
07171700	3.10	3.42	45.46	0.70	1.90	0.94	1857.2	36.25
07171800	0.55	1.70	147.81	0.70	0.81	1.65	575.9	35.69
07171900	19.52	10.38	21.03	0.78	5.10	0.46	5776.3	36.41
07180300	0.58	1.54	51.28	0.61	1.08	1.31	486.7	33.33
07182520	8.23	6.57	12.97	0.69	4.42	0.52	2720.4	37.90
07183800	13.13	6.46	15.72	0.77	4.10	0.55	4637.9	42.25
07184600	26.63	10.03	9.05	1.09	6.58	0.39	6590.7	42.67

Appendix B: Derivation of the Extrapolation Method for Rainfall Depths with ARI = 0.545 Years

To extrapolate the depths for ARI = 0.545 year, we fit a Gumbel distribution (Eq. B-1) to the 1-yr and 2-yr depths.

$$x = \zeta - \alpha \cdot \ln(-\ln(p))$$ **Equation B-1**

where α and ζ are the Gumbel parameters and p is the nonexceedance probability (p = 1 – AEP).

For ARI = 1 year, the AEP is equal to:

$$AEP = 1 - \frac{1}{\exp\left(\frac{1}{ARI}\right)} = 1 - \frac{1}{\exp\left(\frac{1}{1}\right)} = 0.6321$$ **Equation B-2**

As such, the non-exceedance probability (p = 1 – AEP = 1 – 0.6321) equals 0.3679. Substitute this p value into Gumbel distribution (Eq. B-1) to obtain:

$$P_{D,ARI=1yr} = \zeta - \alpha \cdot \ln(-\ln(0.3679)) = \zeta + 5.588 \cdot 10^{-5} \cdot \alpha$$ **Equation B-3**

Where $P_{D,ARI=1yr}$ is the rainfall depth for given duration, D, for ARI = 1 year. Similarly, for an ARI= 2 year, we have

$$AEP = 1 - \frac{1}{\exp\left(\frac{1}{2}\right)} = 0.3935$$ **Equation B-4**

so p = 0.6065 and:

$$P_{D,ARI=2yr} = \zeta - \alpha \cdot \ln(-\ln(0.6065)) = \zeta + 0.6930 \cdot \alpha$$ **Equation B-5**

where $P_{D,ARI=2yr}$ is the rainfall depth for given duration, D, for ARI = 2 years. Subtracting Eq. B-3 from B-5 yields:

$$\alpha = \frac{(P_{D,ARI=2yr} - P_{D,ARI=1yr})}{0.6930 - 5.588 \cdot 10^{-5}} = \frac{(P_{D,ARI=2yr} - P_{D,ARI=1yr})}{0.6930}$$ **Equation B-6**

Substituting Eq. B-6 back into B-3 gives:

$$\zeta = P_{D,ARI=1yr}$$ **Equation B-7**

Substituting Eq. B-6 and B-7 into B-1 and solving for the rainfall depth associated with an ARI = 0.545 years = 6.5 months (which is the event with an AEP of 0.84) gives:

$$P_{D,ARI=0.545yr} = 1.874 \cdot P_{D,ARI=1yr} - 0.874 \cdot P_{D,ARI=2yr}$$ **Equation B-8**

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