UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

DEVELOPMENT OF BANKFULL DISCHARGE AND CHANNEL GEOMETRY RELATIONSHIPS FOR NATURAL CHANNEL DESIGN IN OKLAHOMA USING A FLUVIAL GEOMORPHIC APPROACH

A THESIS

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By

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1.0 Introduction

For many years, the most common approaches to stream bank erosion problems have utilized hard control. Concrete, riprap, gabion baskets, used tires and even car bodies have been used in attempts to prevent bank erosion and control streams and rivers. Too often, these traditional approaches significantly alter the sediment transport characteristics of the stream or river they were designed to control and thus require extensive maintenance, or they result in failure. They can also be detrimental to aquatic life and tend to be unsightly. Even so, many of these techniques continue to be used and taught throughout the country (Biedenharn, et al., 1997).

More recently "bio-engineering" techniques pioneered by the Soil Conservation Service in the 1930's, with traces back to ancient Egypt, are utilizing vegetation to prevent or reduce stream bank erosion (Riley, 1998). Some of these techniques are also being taught across the country and will undoubtedly be used more extensively in the future (International Erosion Control Association, 1996).

Until fairly recently, however, there has been very little understanding of, or concern for, the natural function of stream systems by those attempting to control them. Engineers and planners whose sole focus has been on flood control have, for the most part, ignored the importance of sediment transport in maintaining channel stability. As a result, many of this nation's creeks, streams and rivers have become unstable and are experiencing accelerated bank erosion, channel aggradation (deposition), channel degradation (down-cutting) or a combination thereof. This loss of dynamic stability has resulted in habitat alteration and destruction and a decline in aquatic species diversity and abundance.

In the last few years there has been an increasing interest in taking a fluvial geomorphic approach to riparian management and stream bank stabilization. A fluvial geomorphic approach, "stresses the concept of achieving stream channel stability consistent with the stream's natural tendencies" (Mueller, et al., 1998). This approach requires that the designer understand what those natural tendencies are, how the stream functions and how it is likely to respond to influences within its watershed. The designer then incorporates those tendencies and functions into “natural” stream restoration and bank stabilization projects.

Proper sizing and layout of a constructed “natural” channel is critical for a successful design. “Regional curves” that relate bankfull discharge and bankfull channel dimensions to drainage area aid in the design of “natural” channels. A newly released document, cooperatively developed among fifteen Federal agencies and partners titled “Stream Corridor Restoration: Principles, Processes, and Practices” (U.S.D.A., 1998), addresses the importance of regional curves, stating, “… additional regional relationships should be developed for specific areas of interest.” Fluvial geomorphic “regional curves”, including bankfull discharge and channel geometry relationships for stream channels in Oklahoma, will be presented in this thesis.

2.0 Background

2.1 Stream Classification

Many researchers have spent countless hours attempting to understand and describe the complex, interrelated and dynamic processes that influence the pattern and character of river systems. Although development of a stream classification system risks over-simplification of a very complex system, it is justified in order to achieve the following engineering and management objectives (Rosgen, 1994):

1. Predict a river's behavior from it's appearance;
2. Develop specific hydraulic and sediment relations for a given morphological channel type and state;
3. Provide a mechanism to extrapolate site-specific data collected on a given stream reach to those of similar character; and
4. Provide a consistent and reproducible frame of reference of communication for those working with river systems in a variety of professional disciplines.

Attempts to classify streams began as early as 1899 when Davis (1899) first divided streams into three classes based on relative stage of adjustment: youthful, mature and old age. Leopold and Wolman (1957) concluded that natural channels form a continuous spectrum of patterns from straight, single-thread channels to multithread, braided systems. Schumm (1963) developed a classification system in which delineation was partly based on channel stability (stable, eroding or depositing) and mode of sediment transport.

Leopold, et al. (1964) proposed that the morphology of a stream or river is influenced by eight major variables including the channel slope, width, depth, discharge, velocity, the roughness of the channel materials, the sediment load and the sediment size. Rosgen (1996) observed that a change in any one of these variables sets up a series of channel adjustments, which leads to a change in the others, resulting in channel pattern alterations. He has developed what is currently the most comprehensive and commonly used stream classification system (Rosgen (1996)). Rosgen's system is based on geomorphic variables including the entrenchment ratio, the "bankfull" width to "bankfull" depth ratio, the sinuosity, the slope of the channel, and the dominant bed material. Fundamental to the Rosgen classification system are the concepts of natural stability and "bankfull".

What is natural stability? Can anything in nature be stable without violating Newton's Second Law of thermodynamics? In the truest sense, the answer is "no". Clearly, throughout the millennia running water has been very significant in shaping the landscape as we now see it. The Grand Canyon provides a great illustration of this. The concept of natural stability therefore must imply dynamic stability. Rosgen defines stream stability as the ability of a stream to pass the water, sediment and detritus delivered by the watershed such that over time the dimension, pattern, and profile are maintained and the stream system neither aggrades nor degrades (Rosgen, 1996). Thus, a stream that laterally migrates, but maintains its bankfull width and width/depth ratio, is considered to exhibit natural stability even though the river is considered to be an "active" or "dynamic" system.

According to Dunne and Leopold (1978), "the bankfull stage corresponds to the discharge at which channel maintenance is the most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels." Thus, the bankfull discharge may more simply be considered the "channel forming flow." It is typically associated with an instantaneous peak discharge that occurs from a few days a year to once every other year. It is often related to a recurrence interval of from 1.0 – 1.8 years, as determined using a flood frequency analysis (Rosgen, 1996, Leopold, 1994, U.S.D.A. Forest Service, 1995, U.S.D.A. 1998). Determination of the bankfull discharge is critical for proper application of the classification system. Indicators of the bankfull level include a significant break in the bank slope, a change in particle size and/or a change in vegetation. Discussions of bankfull discharge indicators and significance are presented by

Leopold et al. (1964), Dunne and Leopold (1978), Andrews (1980), Rosgen (1996), and Leopold (1994). A field guide for determining the bankfull stage and conducting a stream channel survey has recently been published by the U.S. Forest Service (Harrelson, et al., 1994). A video demonstrating how to identify the bankfull stage is also available from the U.S.D.A. Forest Service (1995).

A summary of Rosgen's stream classification system is presented in Figure 1. The width/depth ratio is the ratio of the bankfull width to the bankfull mean depth. The entrenchment ratio describes the vertical containment of the stream, or river, and the degree to which it is incised in the valley floor (Kellerhals et al., 1972). It is defined as the ratio of the width of the "flood-prone area" to the bankfull width. The flood-prone area is defined as the width of the channel at an elevation determined at twice the maximum bank-full depth (Rosgen, 1996). Figure 2 illustrates how to determine entrenchment.

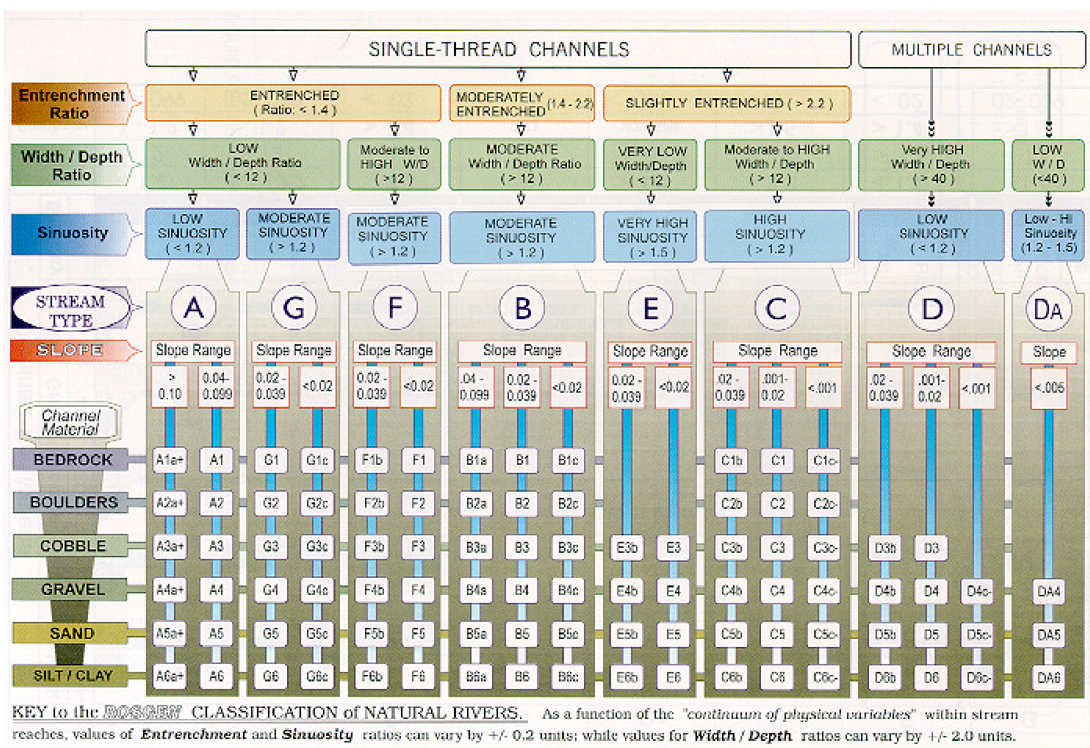

Figure 1: Rosgen's stream classification system (Rosgen, 1996).

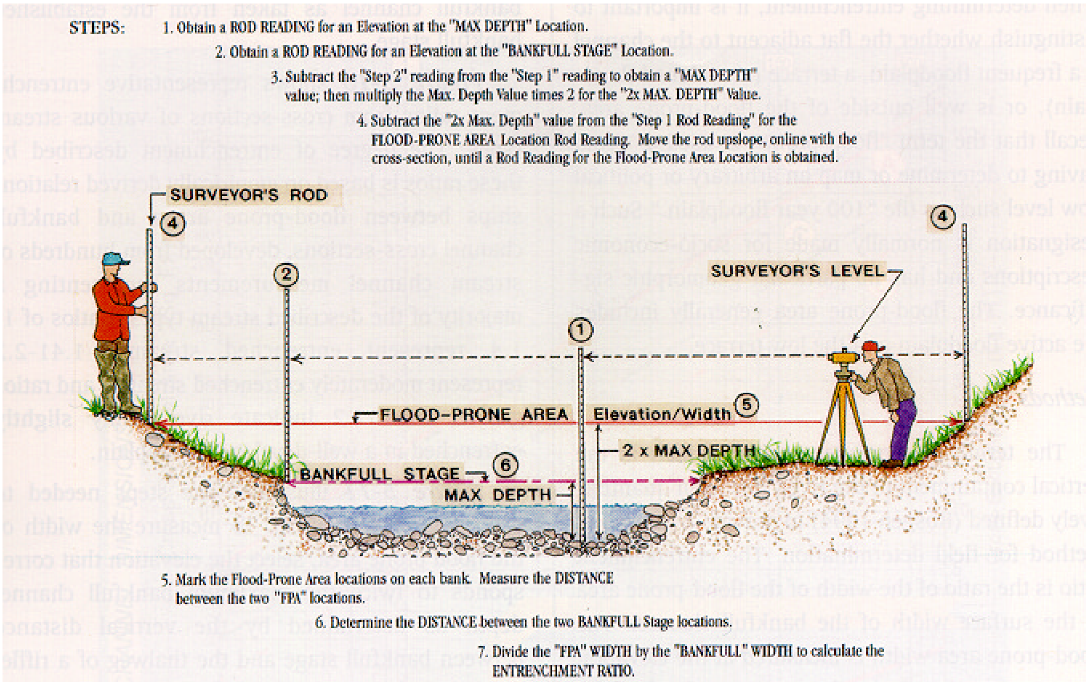

Figure 2: Determining a Flood-Prone Area for calculating the Entrenchment Ratio (Rosgen, 1996).

Sinuosity is a parameter describing the meander pattern of a stream or river. It is defined as the ratio of channel length to valley length (straight-line distance). It can also be described as the ratio of the valley slope to the channel slope (Rosgen, 1996). Two additional design parameters, closely related to sinuosity, are the meander length and the radius of curvature. The meander length is the straight-line length for one complete meander cycle and the radius of curvature is the radius of the bends.

Another important parameter describing the pattern of natural channels is the meander width ratio, defined as the ratio of the belt width to the bankfull width of the channel. A significant result of Rosgen's classification system is the fact that the meander width ratio is linked to stream type. Thus, if the desired stream type is known, the most probable state of channel pattern may be determined and used in stream restoration efforts. These relationships are shown schematically in Figure 3.

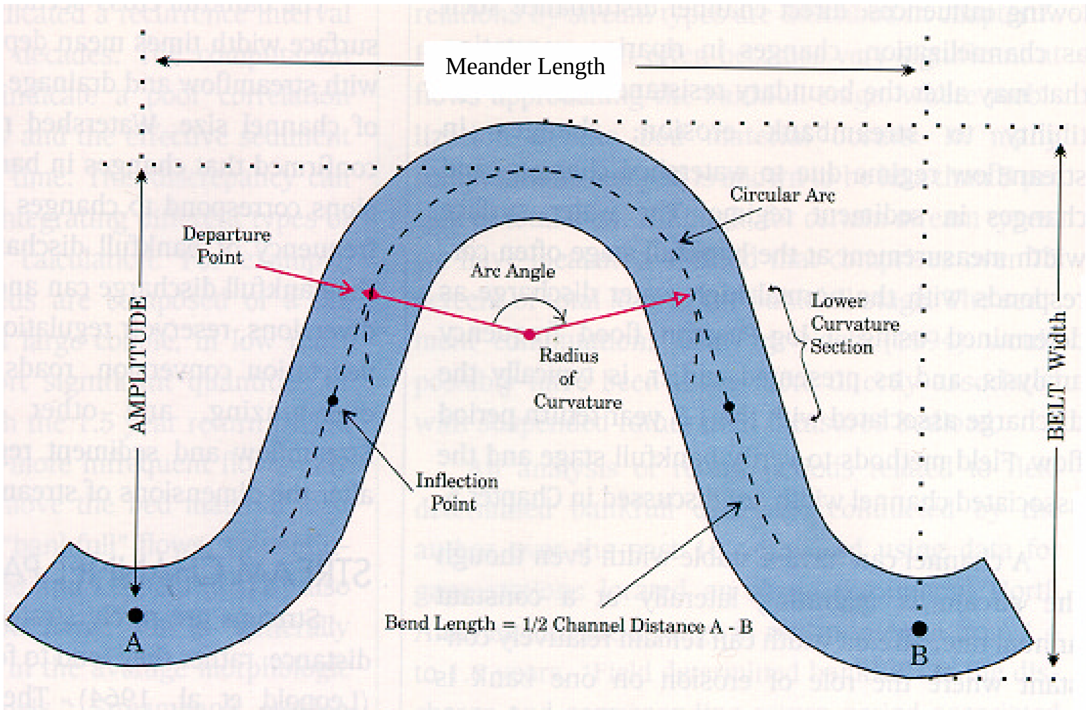

Figure 3: Meander Geometry Schematic (Rosgen, 1996).

Channel material identification is accomplished using the "pebble count" method presented by Wolman (1954). The method involves measuring the intermediate axis of a minimum of 100 particles selected on the “first blind touch” to avoid potential bias. The segmented particle size data is then added together for a composite total. The data may then be effectively plotted on lognormal graph paper to determine the dominant bed material, D50 (the particle size for which 50% of the sample is equal to or smaller than).

This summarizes the parameters required to classify a stream according to the Rosgen classification system. In addition to the parameters required to classify a stream, researchers have identified other characteristics of natural channels. Langbein and Leopold (1966) empirically derived the following relationship between radius of bend curvature (R_c), channel sinuosity (K) and meander length (L_m):

$$R_c = \frac{L_m K^{1.5}}{13(K-1)^{0.5}} \qquad \text{(Eq.1)}$$

Using Equation 1, Williams (1986) found good correlation between observed and predicted values of radius of bend curvature for 79 streams. Leopold (1994) also found that there is a good relationship between meander length and channel width and between meander length and mean radius of curvature (Figure 4).

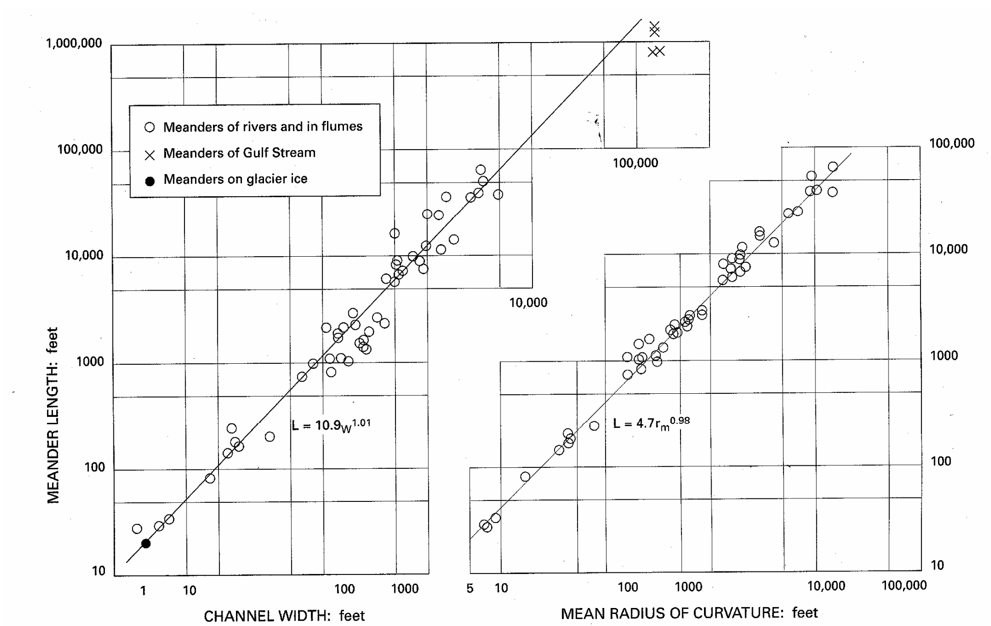

Figure 4: Relations between meander length and channel width, and between meander length and mean radius of curvature (Leopold, 1994).

Equation 2 gives the relationship between meander length (L_m) and channel width (W) and Equation 3 gives the relationship between meander length (L_m) and mean radius of curvature R_c for the plots observed in Figure 4. The equations are applicable to glacial ice and the Gulf Stream as well as streams and rivers and show that the radius of curvature in a natural channel is approximately 2.3 times the channel width.

$$L_m = 10.9W^{1.01} \qquad \text{(Eq. 2)}$$

$$L_m = 4.7R_c^{0.98} \qquad \text{(Eq. 3)}$$

Rosgen's stream classification system, in combination with Equations 1, 2 and 3, can be used as the basis for designing the plan form of a "natural" channel. However, before this can be accomplished, the pattern, or cross-sectional geometry of the channel, must be determined in order to determine the bankfull width. Fluvial geomorphic "regional curves" that relate bankfull discharge and channel geometry to the drainage area are essential for this process.

2.2 Regional Curves

Dunne and Leopold (1978) present some regional curves that show bankfull dimensions versus drainage area for various hydro-geographic provinces (Figure 5). The relationship between bankfull cross-sectional area, bankfull width and bankfull mean depth vs. drainage area are plotted for four different hydro-geographic provinces including the San Francisco Bay region, the Eastern United States, the Upper Green River in Wyoming and the Upper Salmon River in Idaho. Similar plots, though not presented, may also be constructed that relate the bankfull discharge to the drainage area.

These curves, though useful for implementing stream restoration projects in the areas for which they were developed, are not applicable to Oklahoma. Rainfall patterns, evaporation rates, geology, topography, and land use patterns in Oklahoma are significantly different than in the San Francisco Bay area, the Eastern United States, Wyoming or Idaho. The morphology of the streams would therefore be expected to reflect these differences. Thus, if stream restoration projects utilizing the principles of fluvial geomorphology are to be successfully implemented in Oklahoma and surrounding states, it is essential that regional curves be developed specifically for streams in these areas.

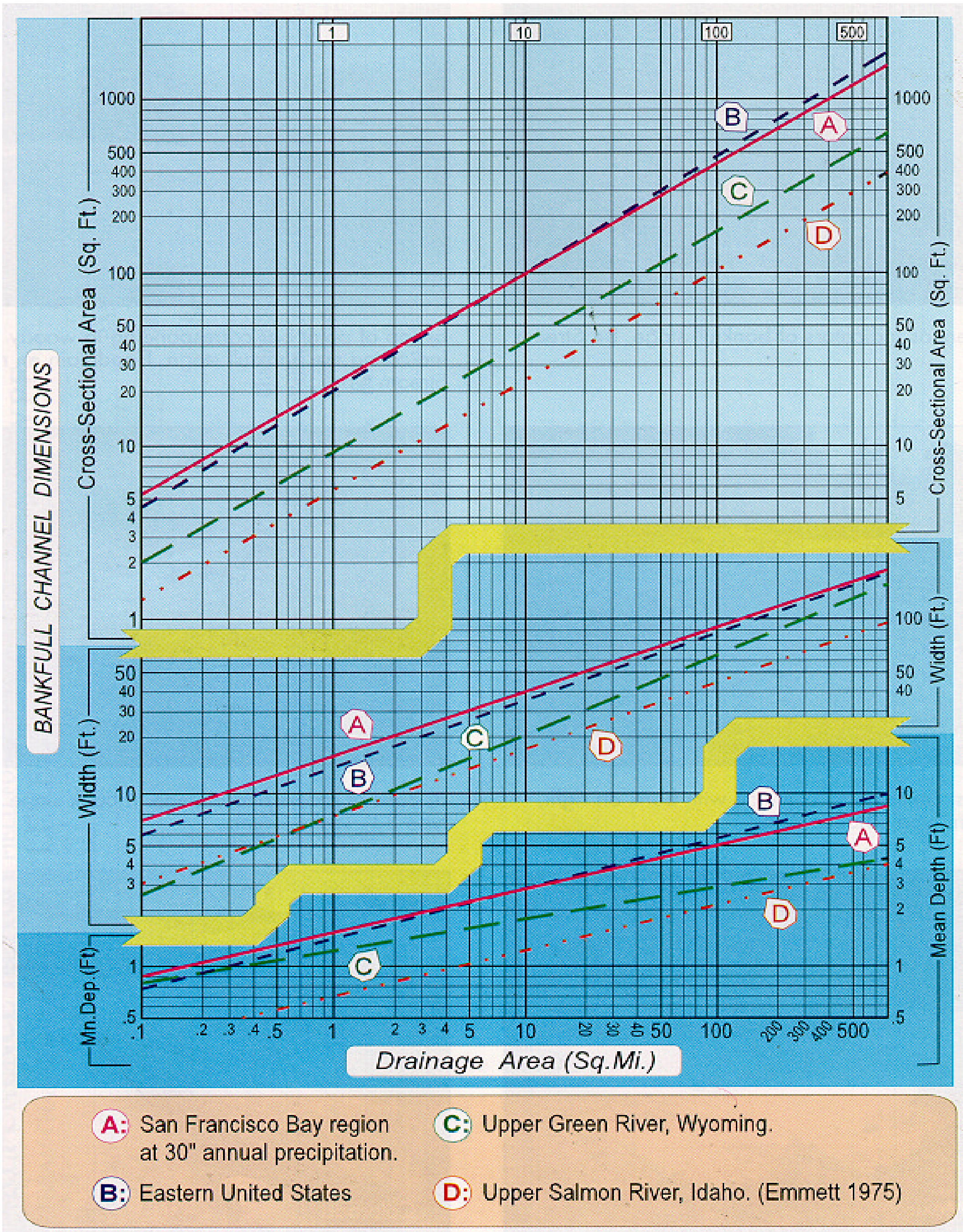

Figure 5: Regional curves showing bankfull dimensions vs. drainage areas for various hydro-physiographic provinces (Rosgen, 1996 after Dunne and Leopold, 1978).

The National Resources Conservation Service (NRCS) has recently released a report in which regional curves relating bankfull cross-sectional area, bankfull width and bankfull depth for the Sugar Creek watershed in southwestern Oklahoma are presented (Mueller, et al., 1998). Figure 6 shows the curves developed by NRCS for the Sugar Creek watershed.

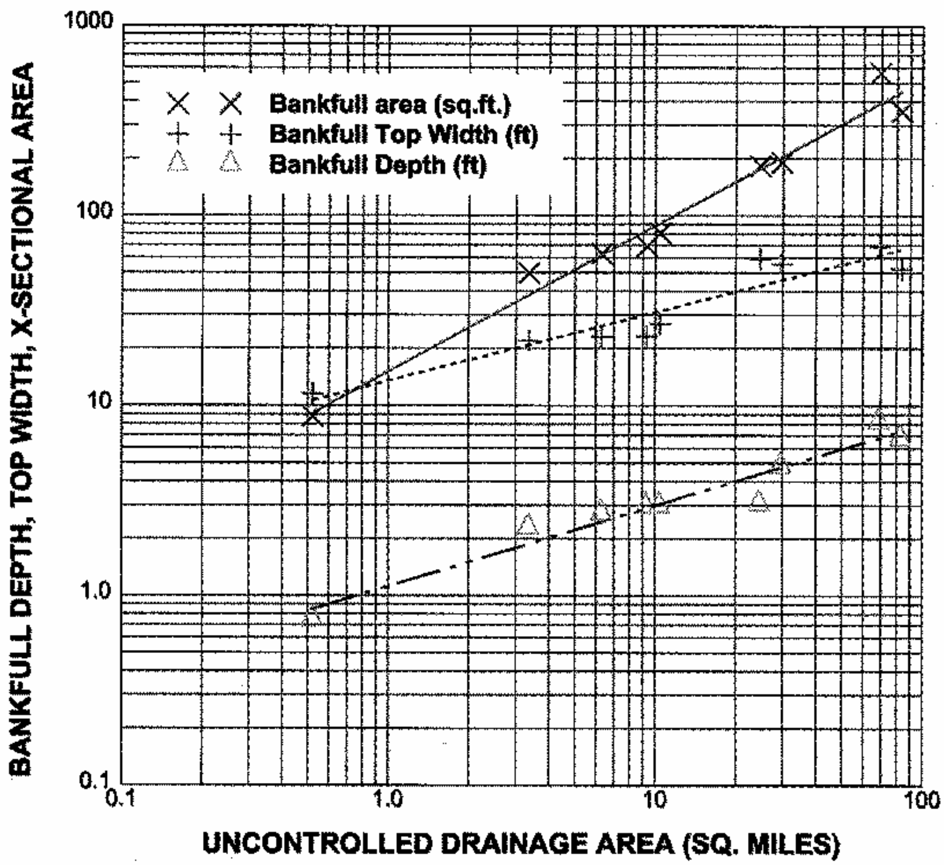

Figure 6: Regional curve developed for the Sugar Creek study (Mueller, et al., 1998).

The Oklahoma Conservation Commission Water Quality Program (OCCWQ) has also been involved with developing regional curves. Regional curves are presented for the Grand Lake basin and northeast Oklahoma (Dutnell, 1998). Relationships were developed for bankfull discharge vs. drainage area, bankfull cross-sectional area vs. drainage area, and bankfull discharge vs. bankfull cross-sectional area.

The NRCS study included assessment at nine USGS gauge stations in the Sugar Creek watershed in Southwest Oklahoma. The OCCWQ study included assessment at six USGS gauge stations in the Grand Lake watershed in northeast Oklahoma, southeast Kansas and southwest Missouri and at an additional four USGS gauge stations in northeast Oklahoma. These studies, though significant, are based on a relatively small data set for only two regions of the state. Additional work is required if fluvial geomorphology is to be successfully used for streambank stabilization projects throughout Oklahoma.

3.0 Study Objectives

The primary objective of this study is to expand on the work initiated by OCCWQ and NRCS and develop regional curves for the entire state of Oklahoma. Upon initiation of this study it was not known how many hydro-geographic provinces there are in the state or how they should be delineated. Secondary objectives were therefore threefold: 1) identify how many hydro-geographic provinces there are in Oklahoma and delineate them, with potential delineations based on average annual rainfall, ecoregion (Omernik, 1987), major river basin (State of Oklahoma, 1992) and climate (USGS, 1999); 2) develop regional curves based on stream type, although it is felt that such delineation may not be meaningful; and 3) estimate the Manning's ("n") roughness coefficient at bankfull for each site surveyed to determine if there is a relationship between stream type and Manning's "n".

4.0 Methodology

Tasks to complete this study included: 1) selecting 40 to 50 USGS gauge stations with sufficient data to establish the bankfull stage and the discharge associated with it; 2) conducting geomorphic surveys at the selected USGS gauge stations to identify the bankfull discharge and channel dimensions; 3) classifying the selected streams using the Rosgen classification method; 4) estimating a Manning's "n" value for each stream selected; and 5) developing the regional curves. The most time consuming task was associated with the fieldwork required to conduct the geomorphic surveys. The methods used to accomplish these tasks are presented below.

4.1 Selection of USGS Gauge Stations

The first task associated with the project was selecting 40 to 50 USGS gauge stations with sufficient data to establish the bankfull discharges and the return periods associated with them. Sites were selected from active USGS gauge stations. Most of the data from active USGS gauge sites are in "real time" and are available over the Internet. Selections were based on the availability of data and to assure adequate spatial coverage of the state. Several sites were surveyed in conjunction with ongoing projects being conducted by the Oklahoma Conservation Commission (OCC) and were included in this study because the data were readily available and because their inclusion increased the size and aerial coverage of the data set. In the end 48, sites were surveyed, 3 were in Kansas, 3 were in Texas, 2 were in Missouri and the remaining 40 were in Oklahoma. In addition, the 10 sites presented by NRCS were included for comparison.

Upon selection of a site, relevant data for the site were obtained from the USGS. Relevant data included the drainage area, the annual peak flow history, and the stage-discharge rating curve for the gauge. The drainage area and the annual peak flow history were typically available on the Internet. The stage-discharge rating curves, however, were obtained directly from the USGS.

4.2 Geomorphic Survey Methods

A geomorphic survey was conducted at each USGS gauge station selected. Geomorphic surveys required fieldwork to collect the data necessary to determine the bankfull discharge and channel dimensions required to classify each stream. Simple surveying techniques, utilizing a laser level and a 300' tape, were applied at each site. Cross-sectional and longitudinal profile surveys were conducted to determine the bankfull width, the mean bankfull depth, the maximum bankfull depth, the bankfull cross-sectional area, the width of the flood prone area, the slope, and the sinuosity of the channel. Channel material identification was accomplished using the "pebble count" method presented by Wolman (1954) unless the dominant bed material was clearly identifiable, in which case it was simply identified visually. A list of equipment needed and a step-by-step method used to conduct geomorphic surveys is presented below.

Equipment needed: field book, pencil, tripod, laser level and receiver, range pole, one hundred foot tape, three hundred foot tape, rebar stakes (¼" dia. X 18" long), hammer, survey flagging, a ruler (marked in millimeters), and a laser range finder (if available).

Step One: Explore the stream. Walk along, or in, the creek noting indicators of the bankfull level (breaks in side slope, changes in vegetation along the channel, and/or changes in particle size). Also look for a representative riffle section in which to establish a cross-section.

Step Two: Establish Cross-section. The cross-section should be located across a representative riffle section. The cross-section is established by hammering rebar pins into the ground on either side of the channel. Place the pins sufficiently back from the edge of the banks so that they will not be lost due to erosion. Flag the pins with survey flagging.

Step Three: Sketch a detailed site map showing distinctive features, the location of the gauge station, the direction of flow, the location of the cross-section and the extent of the reach being surveyed.

Step Four: Stretch the 300-foot tape between the rebar pins marking the ends of the cross-section. The pin on the left side of the channel (facing downstream) is typically located on the zero end of the tape. It helps to have extra rebar stakes to attach the tape to. Tighten the tape as much as possible without breaking the tape. If it is windy, it helps to tie pieces of survey flagging on the tape at random distances to dampen the wind-induced vibration. This will reduce the forces on the tape and minimize the chance of it breaking.

Step Five: Set up the tripod. Mount the laser level on the tripod and level it using the screws on the bottom of the unit.

Step Six: Establish a reference datum for the site. This is typically done by assigning a reference elevation on the left pin as 100 feet (datum). Elevations do not need to be tied to actual elevations, as all data will be relative to the datum. If desired however, the elevations may be tied to a known elevation.

Step Seven: Conduct the cross-sectional survey. This is accomplished by taking a rod reading at every significant break in slope across the channel. In addition, rod readings should be taken at any feature identified as a potential bankfull level, on the existing water surface and at the thalweg (the deepest part of channel).

Step Eight: Identify the extent of the flood prone area. The techniques used to establish the flood prone area are provided in Figure 2.

Step Nine: Conduct the longitudinal profile survey. This is accomplished by taking rod readings on the thalweg, the water surface and any identified bankfull feature at several points longitudinally along the channel. Distances are measured along the thalweg of the channel, and readings should be taken at sufficient distances to characterize the longitudinal profile of the channel. Distances measured downstream from the cross-section are typically assigned positive values and distances upstream are typically assigned negative values. The longitudinal profile should typically extend at least ten bankfull widths or one full meander length (See Figure 3). If it initiates in a riffle it should end in a riffle. Similarly, if it begins in a pool then it should end in a pool.

Step Ten: Determine the valley length for the reach of channel surveyed. This is determined by measuring the straight-line distance between the upstream and downstream end points of the longitudinal profile survey using either a tape or the laser range finder. In some cases this may be extremely difficult and time consuming to accomplish. Therefore, if recent aerial photographs are available for the site, this step may be omitted.

Step Eleven: Identify the dominant bed material. This is accomplished using the "pebble count" method presented by Wolman (1954) unless the dominant bed material is clearly identifiable, in which case it is simply identified visually.

This summarizes the methods utilized to perform the geomorphic surveys conducted in this study. Complete geomorphic assessments of the streams including evaluation of stream stability were not conducted due to time constraints and because it was not required to meet the objectives of this study. Additional information on conducting geomorphic surveys is provided by Rosgen (1996) and the USDA Forest Service (Harrelson, et al., 1994).

The geomorphic surveys in this study were all conducted near a USGS gauge station. Since USGS gauge sites are typically located at bridge crossings, the actual surveys were conducted either upstream or downstream of the gauge at a sufficient distance so that the hydraulics in the stream at the location being surveyed was not impacted by any existing structure.

4.3 Stream Classification Methods

The data obtained from the geomorphic surveys were first used to classify the stream using the Rosgen classification method. As previously mentioned, the parameters required by the Rosgen classification system include the entrenchment ratio, the width/depth ratio, the sinuosity, the slope and the dominant bed material (See Figure 1). For each site, the raw data obtained from the geomorphic survey was entered into a spreadsheet (QuatroPro or Excel). The spreadsheet was then used to plot cross-sections and longitudinal profiles and to calculate the bankfull width, the bankfull cross-sectional area, the bankfull depth (bankfull cross-sectional area/bankfull width), the entrenchment ratio, and the longitudinal slope of the channel.

The entrenchment ratio was determined by taking the ratio of the flood prone area width (as determined in Step Eight, above) to the bankfull width. The bankfull width is the top width of the channel at the bankfull elevation. In cases where the flood prone area width was obviously greater than 2.2 times the bankfull width, the entrenchment ratio was simply identified as >2.2. The Width/depth ratio was determined by taking the ratio of the bankfull width to the bankfull mean depth. The bankfull mean depth was determined by dividing the bankfull cross-sectional area by the bankfull width.

Sinuosity was obtained using one of two methods. The preferred method was to divide the channel length surveyed in the longitudinal survey (Step Nine) by the valley length obtained in Step Ten. However, in several instances, measurements from aerial photographs were used to determine sinuosity at several sites due to the excess amount of time required to survey a reach of stream long enough to accurately determine the sinuosity. However, care was exercised to assure that the aerial photograph was fairly recent (< 5 years) and that the channel had not changed significantly since it was taken. The slope of the channel was determined by dividing the difference between the elevations at the upstream end of the survey and the downstream end by the channel length surveyed. The dominant channel materials were determined using the Wolman “pebble count” method (Wolman, 1954). Once these values were determined from data obtained in the geomorphic survey, the stream was classified using the Rosgen classification method (Figure 1).

4.4 Manning’s “n” Determination Methods

In addition to providing the data necessary to classify the streams, the geomorphic surveys also provided the data necessary to estimate the Manning’s roughness coefficient. (n). The Manning’s equation may be written as:

$$Q = 1.49\,(R)^{2/3}\,(S)^{1/2}\,A / n \qquad \text{(Eq. 4)}$$

where; Q = Discharge (cfs)

R = Hydraulic Radius (ft)

S = Slope (ft/ft)

A = Cross-sectional area (ft^2)

n = Mannings’ roughness coefficient

Since the geomorphic survey provided all of the information required in the equation except the Manning’s roughness coefficient, it was possible to back calculate Manning’s “n” for each stream surveyed. Developing a relationship between stream type and Manning’s “n” would allow one to estimate Manning’s “n” at “bankfull” for various stream types. Rosgen (1994) has done this, and he presents typical values of Manning’s “n” for various stream types that he gathered from 128 surveys.

4.5 Regional Curve Development Methods

The primary objective of this study, as previously stated, is to develop regional curves for the state of Oklahoma. Data from the geomorphic surveys, together with gauge data obtained from the USGS, was used to calculate the bankfull stage, the bankfull discharge and the return interval associated with the bankfull discharge for each site.

The stage and discharge of the stream at the time the survey was conducted was downloaded off of the Internet for the gauge site that was surveyed. The bankfull stage was then determined by taking the difference between the bankfull elevation and the water surface elevation obtained from the cross-section survey and adding the value obtained to the stage of the stream at the time the survey was conducted. The stage-discharge rating curve for the gauge was then used to determine the bankfull discharge associated with the bankfull stage. The return interval of the estimated bankfull discharge was then estimated using the annual peak flow analysis obtained from the USGS. The return interval was used as a check of the assumed bankfull discharge, as it has been determined that the recurrence interval of the bankfull discharge is typically between 1.0 and 1.8 years (Leopold, 1994, Rosgen, 1994, USDA, 1998).

Pertinent results for each site were then entered into a summary spreadsheet, which included the following: the site number, the USGS gauge station name, the USGS gauge station number, the legal description, the latitude and longitude, the County, the mean annual precipitation, the ecoregion, the river basin, the climate region, the drainage area at the gauge, the bankfull discharge, the return interval associated with the bankfull discharge, the bankfull width, the bankfull depth, the bankfull cross-sectional area, the width/depth ratio, the entrenchment ratio, the sinuosity, the longitudinal slope and the stream type. Relevant comments about the site were also entered.

The summary spreadsheet was then used to sort the data by stream type, river basin, climate zone, mean annual precipitation and ecoregion. Plots showing the relationships for bankfull discharge versus drainage area, bankfull cross-sectional area versus drainage area, bankfull width versus drainage area, bankfull mean depth versus drainage area, and bankfull discharge versus bankfull cross-sectional area were then developed for each sorting. The Excel "linest" function was then used to develop regression equations and calculate the coefficient of determination, R^2, for each regional curve. Appropriate hydro-geographic provinces were then identified and delineated after evaluating the data from the various plots.

Note that the coefficient of determination compares estimated and actual y-values. It ranges in value from 0 to 1. If it is 1, there is a perfect correlation in the sample (i.e., there is no difference between the estimated y-value and the actual y-value). At the other extreme, if the coefficient of determination is 0, the regression equation is not helpful in predicting a y-value. The coefficient of determination is therefore a measure of the "goodness of fit" of the equation to the data. For the purpose of this study, a coefficient of determination, R^2, of less than 0.6 is considered a "poor" fit, between 0.6 and 0.7 is considered a "fair" fit, between 0.7 and 0.8 is considered a "good" fit, between 0.8 and 0.9 is considered a "very good" fit, and greater than 0.9 is considered an "excellent" fit.

5.0 Results

The results of the study are presented below. A brief presentation of the selected sites is followed by the results of the geomorphic surveys and stream classification. Presentation of the regional curves developed in this study, including a discussion on the potential delineation of hydro-geographic provinces based on climate division, ecoregion, river basin and/or mean annual precipitation is then given.

5.1 Site Selection

A total of 48 sites were surveyed for this study. Geomorphic surveys were conducted at sites in 32 of Oklahoma's 77 counties, in 3 counties in Kansas, 2 counties in Missouri and 2 counties in Texas. In addition, the 10 sites presented by NRCS were included for comparison. The locations of the geomorphic survey sites, except for the 3 sites located in Texas, are shown in Figure 7. The numbers shown in Figure 7 are reference numbers assigned sequentially to each site as it was surveyed for this project.

Table 1 gives a list of the sites where geomorphic surveys were conducted. The table gives the reference number for the site, the USGS gauge name and number for the gauge station where the survey was conducted, the latitude and longitude of the site and the county where the site is located. Site descriptions for each site surveyed are provided in Appendix A.

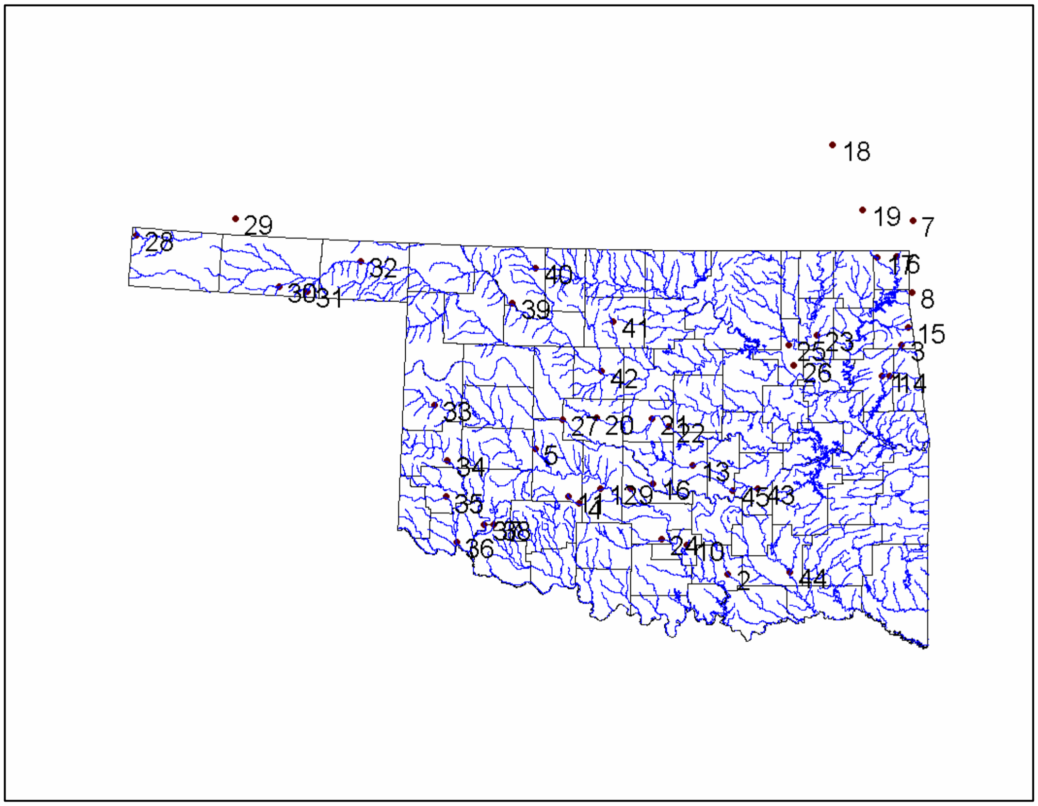

Figure 7: Location of geomorphic survey sites.

5.2 Geomorphic Surveys and Stream Classification

The results of the geomorphic surveys and stream classification are presented in Table 2. The table shows the reference number for the site, the USGS gauge name, the width/depth ratio, the entrenchment ratio, the sinuosity, the longitudinal slope and the stream type for each site surveyed. Survey data for each site are provided in Appendix A. Cross-sectional and longitudinal profile plots for most sites are provided in Appendix B. Photographs of many of the sites are provided in Appendix C, although pictures are not available for all sites, as some were lost due to inadvertent dunking of the camera.

Table 1: List of Geomorphic Survey Sites.

No.	Gauge Station Name	USGS Gauge Station No.	Latitude Deg, Min, Sec, N	Longitude Deg, Min, Sec, W	County
1	Illinois River at Tahlequah	07196500	35 55 22	94 55 24	Cherokee
2	Blue River at Milburn	07332400	34 15 04	96 33 05	Johnston
3	Flint Creek near Kansas	07196000	36 11 11	94 42 24	Delaware
4	Little Washita River near Cement	07327447	34 50 16	98 07 27	Comanche
5	Cobb Creek near Eakley	07325800	35 17 26	98 35 38	Caddo
6	Spring River at Quapaw	07188000	36 56 04	94 44 46	Ottawa
7	Spring River near Waco, MO	07186000	37 14 44	94 33 58	Jasper,MO
8	Elk River near Tiff City, MO	07189000	36 37 53	94 35 12	Mcdonald,MO
9	North Criner Creek near Criner	07328180	34 58 17	97 35 04	McClain
10	Rock Creek near Sulpher	07329852	34 29 43	96 59 18	Murray
11	Little Washita River near Cyril	07327442	34 53 32	98 13 58	Caddo
12	Little Washita River nr E.Ninekah	07327550	34 57 48	97 53 57	Grady
13	Little River near Tecumseh	07230500	35 10 21	96 55 54	Pottawotamie
14	Baron Fork at Eldon	07197000	35 55 16	94 50 18	Cherokee
15	Spavinaw Creek near Sycamore	07191220	36 20 07	94 38 27	Delaware
16	Canadian River at Purcell	07229200	35 00 50	97 20 50	Cleveland
17	Neosho River near Commerce	07185000	36 55 43	94 57 26	Ottawa
18	Neosho River at Iola, KS	07183000	37 53 27	95 25 50	Allen, KS
19	Neosho River near Parsons, KS	07183500	37 20 24	95 06 35	Labette,KS
20	N. Canadian at El Reno	07239500	35 33 47	97 57 26	Canadian
21	N. Canadian at Britton Rd	07241520	35 33 56	97 22 01	Oklahoma
22	N. Canadian near Harrah	07241550	35 30 01	97 11 37	Oklahoma
23	Dog Creek near Claremore	07178520	36 16 43	95 36 40	Rogers
24	Wildhorse Creek near Hoover	07329700	34 32 29	97 14 49	Garvin

Table 1: List of Geomorphic Survey Sites (Continued).

No.	Gauge Station Name	USGS Gauge Station No.	Latitude Deg, Min, Sec, N	Longitude Deg, Min, Sec, W	County
25	Coal Creek at Tulsa	07177800	36 11 40	95 54 50	Tulsa
26	Little Haikey Creek at Tulsa	07165565	36 01 03	95 51 38	Tulsa
27	Canadian River at Bridgeport	07228500	35 32 37	98 19 03	Caddo
28	Cimarron River near Kenton	07154500	36 55 36	102 57 31	Cimarron
29	Cimarron River near Elkhart, KS	07155590	37 07 30	101 53 50	Morton,KS
30	Coldwater Creek near Guymon	07232900	36 34 19	101 22 52	Texas
31	Palo Duro Creek at Range	07233650	36 32 38	101 04 50	Texas
32	Beaver River at Beaver	07234000	36 49 20	100 31 08	Beaver
33	Washita River near Cheyenne	07316500	35 37 35	99 40 05	Roger Mills
34	N. Fork of Red River near Carter	07301500	35 10 05	99 30 25	Beckham
35	Salt Fork of Red River at Mangum	07300500	34 51 30	99 30 30	Greer
36	Salt Fork of Red River near Elmer	07301110	34 28 44	99 22 55	Jackson
37	N. Fork of Red River near Headrick	07305000	34 38 04	99 05 47	Tillman
38	Otter Creek near Snyder	07307010	34 38 16	98 59 54	Kiowa
39	Cimarron River near Waynoka	07158000	36 31 02	98 52 45	Woods
40	Salt Fork of Ark. River near Alva	07148400	36 48 54	98 38 52	Woods
41	Skeleton Creek near Enid	07160350	36 22 34	97 48 00	Garfield
42	Cimarron River near Dover	07159100	35 57 06	97 54 51	Kingfisher
43	Canadian River at Calvin	07231500	34 58 40	96 14 36	Hughes
44	Muddy Boggy Creek near Farris	07334000	34 16 17	95 54 43	Atoka
45	Little River near Sasakwa	07231000	34 57 55	96 30 44	Seminole
46	Llano River near Junction,TX	08150000	30 30 15	99 44 03	Kimble, TX
47	San Sabo River at Menard, TX	08144500	30 55 08	99 47 07	Menard,TX
48	North Llano River near Junction,TX	08148500	30 31 06	99 48 39	Kimble,TX

Table 2: Stream Classification Data for Geomorphic Survey Sites.

No.	Gauge Station Name	W/D	Entr.	Sin.	Slope, ft/ft	Type
1	Illinois River at Tahlequah	23.19	>2.2	1.02	0.00013	C4c-
2	Blue River at Milburn	19.45	>2.2	1.28	0.00079	C5c-
3	Flint Creek near Kansas	57.37	1.60	1.09	0.00056	B4c
4	Little Washita River near Cement	9.83	1.32	1.26	0.00067	G5c
5	Cobb Creek near Eakley	9.82	>2.2	1.35	0.00076	E5
6	Spring River at Quapaw	19.37	>2.2	1.05	0.00002	C5c-
7	Spring River near Waco, MO	30.90	1.31	1.02	0.00009	F4
8	Elk River near Tiff City, MO	22.13	>2.2	1.08	0.00085	C4
9	North Criner Creek near Criner	6.61	1.67	1.09	0.00220	B5c
10	Rock Creek near Sulpher	17.69	>2.2	1.06	0.00156	C1
11	Little Washita River near Cyril	8.14	>2.2	1.03	0.00983	E5
12	Little Washita River nr E.Ninekah	22.57	1.49	1.08	0.00112	B5c
13	Little River near Tecumseh	21.30	1.38	~1.00	0.00052	F5
14	Baron Fork at Eldon	41.29	>2.2	1.07	0.00167	C4
15	Spavinaw Creek near Sycamore	32.71	>2.2	1.38	0.00190	C4
16	Canadian River at Purcell	230.16	>2.2	1.09	0.00079	C5
17	Neosho River near Commerce	54.32	1.03	1.01	0.00320	F1
18	Neosho River at Iola, KS	24.25	1.16	1.83	0.00182	F4
19	Neosho River near Parsons, KS	18.72	1.95	1.41	0.00418	B5c
20	N. Canadian at El Reno	14.82	>2.2	1.54	0.00066	C5c-
21	N. Canadian at Britton Rd	56.62	>2.2	1.31	0.00045	C5c-
22	N. Canadian near Harrah	19.36	>2.2	1.18	0.00050	C5c-
23	Dog Creek near Claremore	8.71	>2.2	1.62	0.00047	E6
24	Wildhorse Creek near Hoover	27.01	1.12	1.15	0.00120	F5

W/D: Width/Depth ratio   Entr.: Entrenchment ratio   Sin.: Sinuosity

Table 2: Stream Classification Data for Geomorphic Survey Sites (Continued).

No.	Gauge Station Name	W/D	Entr.	Sin.	Slope, ft/ft	Type
25	Coal Creek at Tulsa	9.97	1.71	1.10	0.00024	B4c
26	Little Haikey Creek at Tulsa	6.52	>2.2	1.72	0.00055	E5
27	Canadian River at Bridgeport	157.77	>2.2	1.05	0.00079	C5c-
28	Cimarron River near Kenton	47.86	>2.2	1.08	0.00140	C5
29	Cimarron River near Elkhart, KS	46.81	>2.2		0.00103	C5
30	Coldwater Creek near Guymon	69.81	>2.2	1.06	0.00195	C5
31	Palo Duro Creek at Range	14.99	>2.2		0.00297	C5
32	Beaver River at Beaver	30.76	>2.2	1.23	0.00063	C5c-
33	Washita River near Cheyenne	39.60	>2.2	1.15	0.00133	C5
34	N. Fork of Red River near Carter	61.48	>2.2	1.24	0.00091	C5c-
35	Salt Fork of Red River at Mangum	97.03	>2.2	1.13	0.00142	C5
36	Salt Fork of Red River near Elmer	38.37	>2.2	1.95	0.00057	C5c-
37	N. Fork of Red River near Headrick	27.85	>2.2	1.21	0.00037	C5c-
38	Otter Creek near Snyder	6.06	>2.2	1.12	0.00069	E5
39	Cimarron River near Waynoka	135.39	>2.2	1.07	0.00101	C5
40	Salt Fork of Ark. River near Alva	17.87	>2.2	1.18	0.00160	C5
41	Skeleton Creek near Enid	16.91	>2.2	1.12	0.00365	C1
42	Cimarron River near Dover	76.34	>2.2	1.14	0.00069	C5c-
43	Canadian River at Calvin	107.17	>2.2	1.09	0.00063	C5c-
44	Muddy Boggy Creek near Farris	9.42	1.67	1.08	0.00017	G5c
45	Little River near Sasakwa	16.15	>2.2	1.08	0.00086	C5c-
46	Llano River near Junction,TX	70.81	1.39	1.21	0.00190	B4c-
47	San Sabo River at Menard, TX	58.13	>2.2	1.31	0.00210	C4
48	North Llano River near Junction,TX	59.02	1.21	1.08	0.00110	F1

W/D: Width/Depth ratio Entr.: Entrenchment ratio Sin.: Sinuosity

The width/depth ratio varied from 6.06 to 230.16, with mean and median values of 42.05 and 25.63, respectively. The entrenchment ration varied from 1.03 to greater than 2.2. The mean and median were not determined, as many values were reported as greater than 2.2. In fact, thirty-four of the forty-eight sites had entrenchment ratios greater than 2.2. The sinuosity varied from 1.01 to 1.95, with mean and median values of 1.21 and 1.12, respectively. The longitudinal slope varied from 0.00002 ft/ft to 0.00983 ft/ft, with mean and median values of 0.00134 ft/ft and 0.00086 ft/ft, respectively.

Thirteen different stream types were identified. There were three B4c's, three B5c's, two C1's, four C4's, one C4c-, nine C5's, thirteen C5c-'s, four E5's, one E6, two F1's, two F4's, two F5's and two G5c's. Four sites had a bedrock substrate, seven had a gravel substrate, and one had a silt substrate. Thirty-three of the forty-eight sites surveyed had sand substrates. No channels were found to have boulder or cobble substrate.

5.3 Regional Curves

Regional curve data for each site are provided in Table 3. Data presented includes the reference number for the site, the USGS gauge name, the drainage area (mi^2), the bankfull discharge (cfs), the return interval associated with the bankfull discharge (years), the bankfull width (ft), the bankfull depth (ft) and the bankfull cross-sectional area (ft^2).

The drainage areas ranged from 5.45 mi^2 to 23,151 mi^2, with mean and median values of 3,275 mi^2 and 984 mi^2, respectively. The bankfull discharges ranged from 136.7 cfs to 41,750 cfs with mean and median values of 5,275 cfs and 3,444 cfs, respectively. Return intervals were not available for 5 sites due to insufficient data. The period of record for these sites was not sufficiently long enough to determine the return interval. The return interval associated with the bankfull discharge ranged from 1.01 years to 3.65 years, with mean and median values of 1.41 years and 1.33 years, respectively. The high value (3.65 years) is outside the expected range and will be discussed later.

Table 3: Regional Curve Data for Geomorphic Survey Sites.

No.	Gauge Station Name	DA, mi^2	Q, cfs	R.I.	W, ft	D, ft	A, ft^2
1	Illinois River at Tahlequah	959	3700	1.05	169.51	7.31	1239.12
2	Blue River at Milburn	203	2569	1.15	150.35	7.73	1162.23
3	Flint Creek near Kansas	110	2692	1.55	133.34	2.32	309.87
4	Little Washita River near Cement	31	667	1.65	38.74	3.94	152.64
5	Cobb Creek near Eakley	132	1494	1.54	67.30	6.85	461.01
6	Spring River at Quapaw	2510	20060	1.24	279.19	14.41	4024.20
7	Spring River near Waco, MO	1164	5122	1.07	162.98	5.28	859.77
8	Elk River near Tiff City, MO	872	10880	1.42	215.99	9.76	2108.29
9	North Criner Creek near Criner	7.33	290.8	1.72	34.51	5.22	180.14
10	Rock Creek near Sulpher	44.1	2376	1.33	43.41	3.89	267.40
11	Little Washita River near Cyril	11.6	225	1.49	18.16	2.23	40.53
12	Little Washita River nr E.Ninekah	236	4760	1.76	66.01	2.92	193.10
13	Little River near Tecumseh	456	3303	1.11	78.93	3.71	292.49
14	Baron Fork at Eldon	307	3638	1.07	169.70	4.11	696.30
15	Spavinaw Creek near Sycamore	133	1704	1.43	129.52	3.96	512.90
16	Canadian River at Purcell	21138	13820	1.39	552.38	2.40	1325.71
17	Neosho River near Commerce	5876	10950	1.01	355.80	6.55	2330.49
18	Neosho River at Iola, KS	3818	8631	1.03	210.68	8.69	1830.59
19	Neosho River near Parsons, KS	4905	10440	1.04	196.19	10.48	2056.00
20	N. Canadian at El Reno	8143	3137	1.75	117.21	7.91	927.13
21	N. Canadian at Britton Rd	8514	6010	1.45	340.26	6.01	2044.96
22	N. Canadian near Harrah	8602	7935	3.65	169.58	8.76	1485.52
23	Dog Creek near Claremore	74.9	744.9	?	58.21	6.68	389.10
24	Wildhorse Creek near Hoover	604	4700	1.11	145.86	5.40	787.64

DA: Drainage area; Q: Bankfull discharge; R.I.: Return interval; W: Bankfull width; D: Bankfull depth; A: Bankfull Area

Table 3: Regional Curve Data for Geomorphic Survey Sites (Continued).

No.	Gauge Station Name	DA, mi^2	Q, cfs	R.I.	W, ft	D, ft	A, ft^2
25	Coal Creek at Tulsa	7.53	1080	1.11	42.17	4.23	178.38
26	Little Haikey Creek at Tulsa	5.45	1011	1.77	43.57	6.69	291.35
27	Canadian River at Bridgeport	20475	10470	1.28	460.77	2.92	1345.73
28	Cimarron River near Kenton	1038	4248	1.90	129.70	2.71	351.49
29	Cimarron River near Elkhart, KS	2406	158.6	1.49	108.60	2.32	251.95
30	Coldwater Creek near Guymon	725	220	2.00	141.71	2.03	287.67
31	Palo Duro Creek at Range	826	310	?	56.98	3.80	216.52
32	Beaver River at Beaver	3685	162.3	1.06	55.99	1.82	101.90
33	Washita River near Cheyenne	794	136.7	1.09	49.89	1.26	62.86
34	N. Fork of Red River near Carter	1938	2882	1.24	209.03	3.40	710.70
35	Salt Fork of Red River at Mangum	1357	2719	1.05	228.02	2.35	535.85
36	Salt Fork of Red River near Elmer	1669	4716	1.29	191.10	4.98	951.68
37	N. Fork of Red River nr Headrick	3845	5844	1.23	172.70	6.20	1070.74
38	Otter Creek near Snyder	217	735.7	?	31.90	5.26	167.79
39	Cimarron River near Waynoka	8504	5917	1.23	361.50	2.67	965.21
40	Salt Fork of Ark. River near Alva	1009	2685	1.20	120.27	6.73	809.42
41	Skeleton Creek near Enid	70.3	3422	?	107.73	6.37	686.24
42	Cimarron River near Dover	10787	16070	1.54	463.38	6.07	2812.72
43	Canadian River at Calvin	23151	41750	1.44	704.09	6.57	4625.87
44	Muddy Boggy Creek near Farris	1087	1856	?	96.41	10.24	987.24
45	Little River near Sasakwa	884	4785	1.22	136.91	8.48	1161.00
46	Llano River near Junction,TX	1855.14	4658	1.44	313.00	4.42	1383.46
47	San Sabo River at Menard, TX	1135	4029	1.79	218.00	3.75	817.50
48	N. Llano River near Junction,TX	914	3465	1.46	229.00	3.88	888.52

DA: Drainage area; Q: Bankfull discharge; R.I.: Return interval; W: Bankfull width; D: Bankfull depth; A: Bankfull Area

The bankfull widths ranged from 18.16 ft to 704 ft, the bankfull depths ranged from 1.26 ft to 14.41 ft, and the bankfull cross-sectional areas ranged from 40.5 ft^2 to 4,626 ft^2. The mean values for the bankfull width, the bankfull depth, and the bankfull cross-sectional area were 178.67 ft, 5.33 ft and 986.23 ft^2, respectively; median values are 143.79 ft, 5.10 ft, and 798.53 ft^2, respectively.

5.3.1. *Entire Data Set*

The bankfull discharge, the bankfull cross-sectional area, the bankfull width and the bankfull depth for the entire data set are plotted versus drainage area in Figures 8-11, respectively. A plot of bankfull discharge versus bankfull cross-sectional area is shown in Figure 12.

A couple of points should be made regarding the bankfull discharge versus drainage area plot given in Figure 8. First, there are four sets of data plotted on this graph. They are referred to as Oklahoma-Region 1, Oklahoma-Region 2, Texas and NRCS. The Oklahoma data was split into two “Regions” after reviewing the initial data plots, as it was fairly obvious that the data from five sites do not fit well with the rest of the data. These five data points, which have site numbers ranging from 29 to 33, are all located in the panhandle or far western Oklahoma, as can be seen in Figure 7. Justification for splitting the data into two groups will be discussed quite extensively later in the thesis. Equation 5 gives the linear regression of all the data:

$$Q = 186.32 * DA^{0.399} \qquad \text{(Eq. 5)}$$

where Q is the bankfull discharge in cubic feet per second and DA is the drainage area in square miles. The coefficient of determination (R^2) for this relationship was determined to be 0.47 as shown in Figure 8. Equation 6 gives the linear regression of the data without the points in Oklahoma-Region 2.

$$Q = 174.66 * DA^{0.458} \qquad \text{(Eq. 6)}$$

Equation 6 has a coefficient of determination (R^2) of 0.80, as shown in Figure 8. A linear regression was not performed for Oklahoma-Region 2 because, unfortunately, there were not enough data points to determine a realistic equation for this area.

The second point that should be made about the bankfull discharge versus drainage area plot given in Figure 8 is in regards to the Texas data. Figure 8 shows six distinct points representing data from three separate gauge stations located in Kimble and Menard counties in west central Texas. These data were collected as part of a training exercise the author presented to NRCS personnel in Texas. These data were included to show the extent of variability in identifying bankfull features that would be encountered by different groups of people. The individuals that performed these surveys had little or no knowledge of fluvial geomorphology, yet their results were all similar. For analysis purposes, only one set of data from each gauge was used for inclusion in the regression equations presented above.

Figure 9 shows a plot of bankfull cross-sectional area versus drainage area for the entire data set. Once again, there are four sets of data plotted on this graph, Oklahoma-Region 1, Oklahoma-Region 2, Texas and NRCS. Equation 7 gives the linear regression of all the data:

$$A = 46.47 * DA^{0.387} \qquad \text{(Eq. 7)}$$

where Q is the bankfull cross-sectional area in square feet and DA is the drainage area in square miles. The coefficient of determination (R^2) for this relationship was determined to be 0.62 as shown in Figure 9. Equation 8 gives the linear regression of the data without the points in Oklahoma-Region 2. The coefficient of determination (R^2) was determined to be 0.77, as shown in Figure 9.

$$A = 44.59 * DA^{0.420} \qquad \text{(Eq. 8)}$$

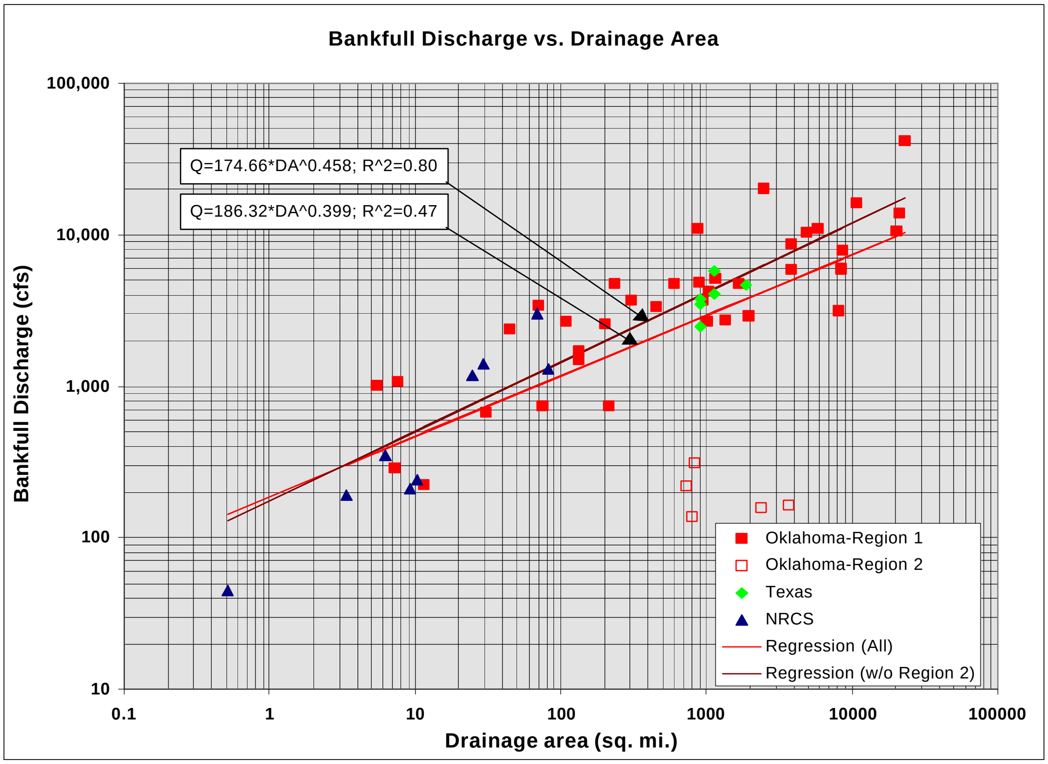

Figure 8: Plot of Bankfull Discharge (cfs) versus Drainage Area (mi^2) – Entire Data Set.

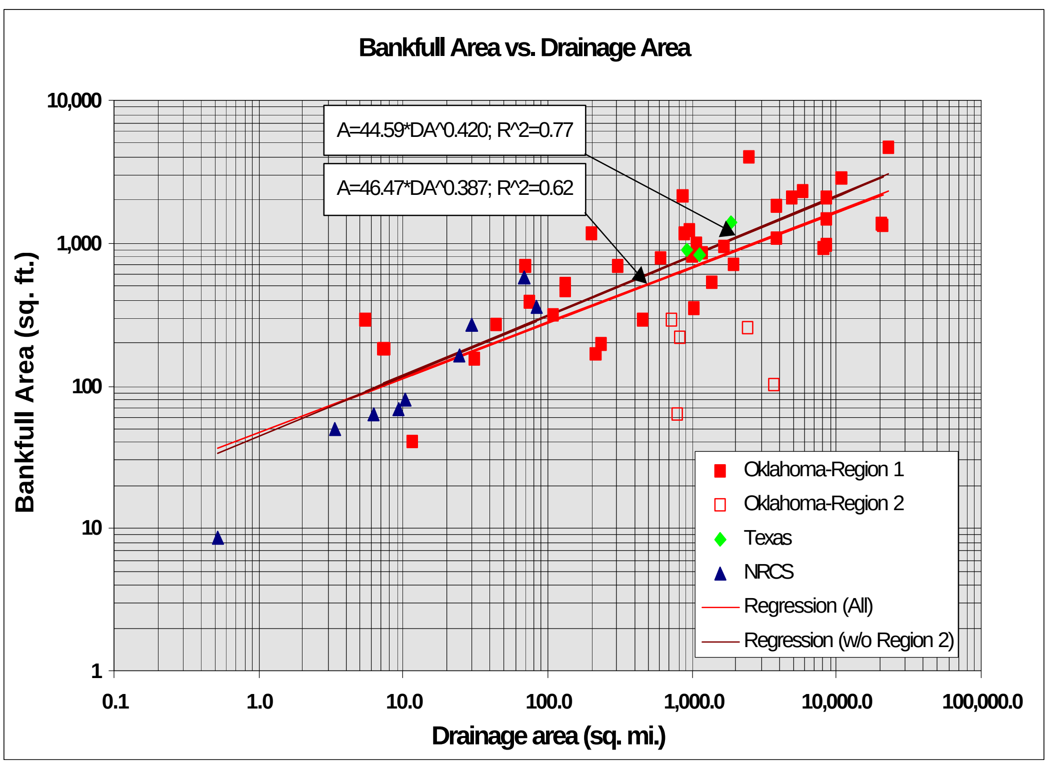

Figure 9: Plot of Cross-sectional Area (ft^2) versus Drainage Area (mi^2) – Entire Data Set.

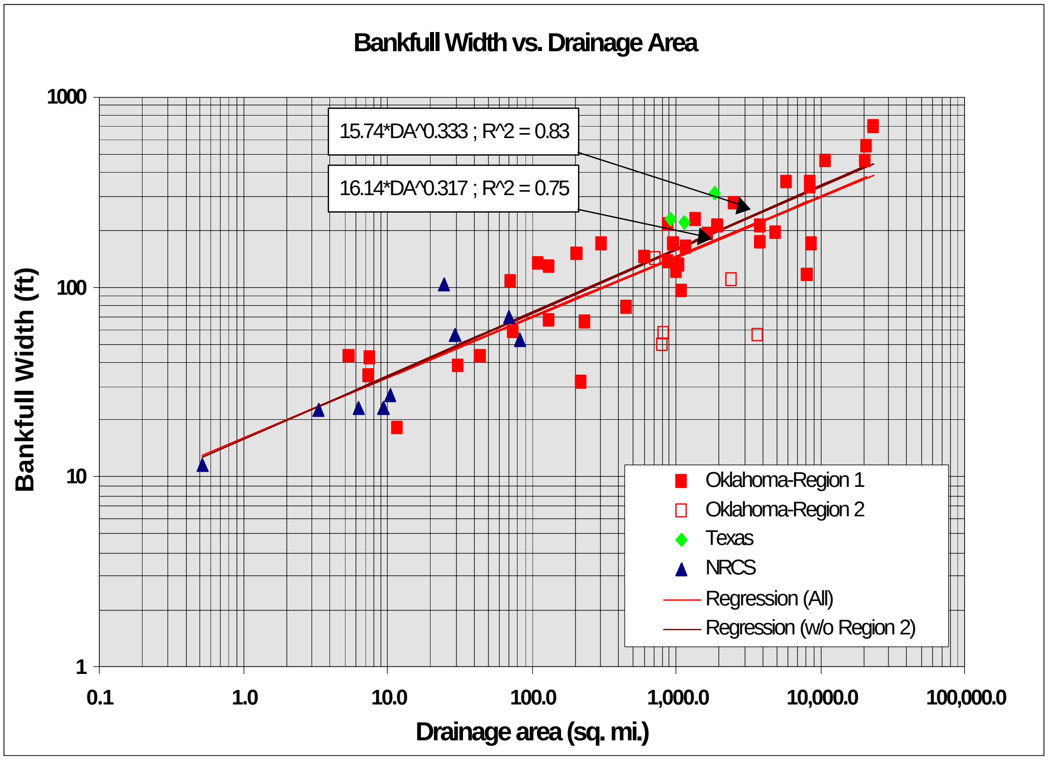

Figure 10: Plot of Bankfull Width (ft) versus Drainage Area (mi^2) – Entire Data Set.

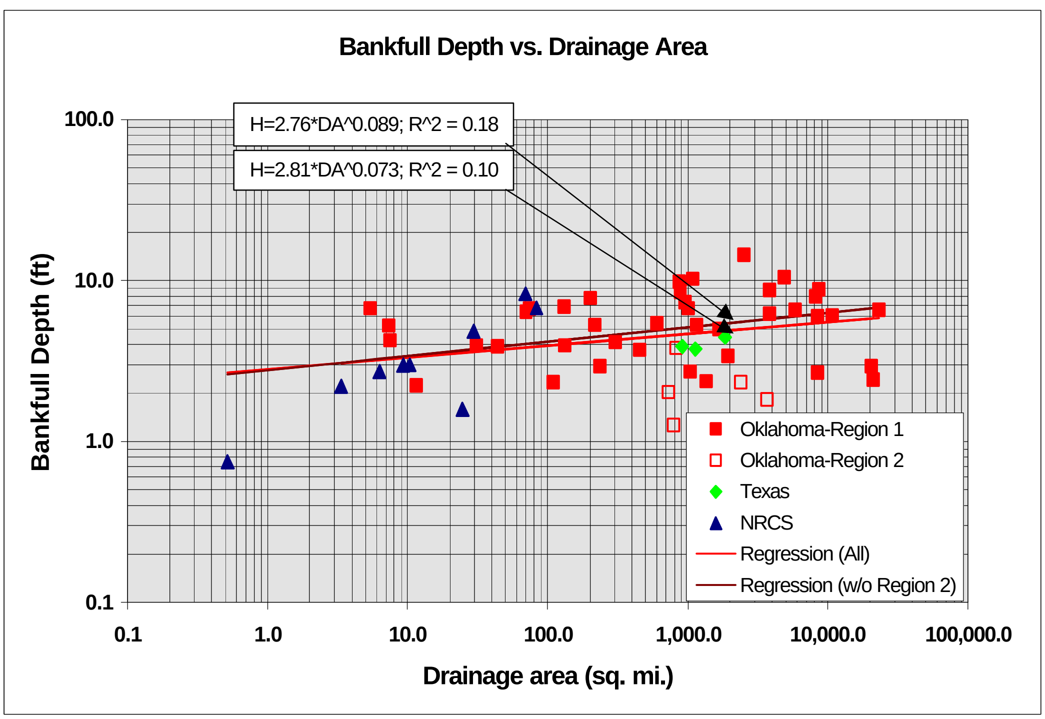

Figure 11: Plot of Bankfull Depth (ft) versus Drainage Area (mi^2) – Entire Data Set.

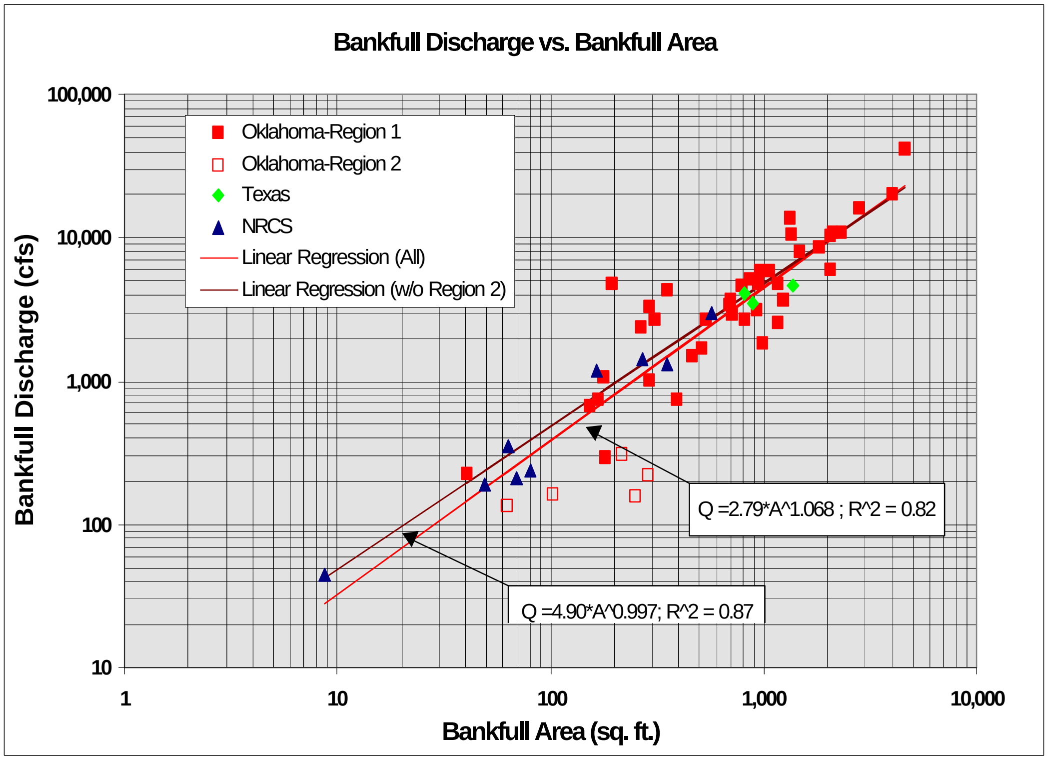

Figure 12: Plot of Bankfull Discharge (cfs) versus Cross-sectional Area (ft^2) -Entire Data Set.

Figure 10 shows a plot of bankfull width versus drainage area. Again, four sets of data are plotted on this graph, Oklahoma-Region 1, Oklahoma-Region 2, Texas and NRCS. Equation 9 gives the linear regression of all the data:

$$W = 16.14 * DA^{0.317} \quad \text{(Eq. 9)}$$

where W is the bankfull width in feet and DA is the drainage area in square miles. The coefficient of determination (R^2) for this relationship was determined to be 0.75 as shown in Figure 10. Removing the data points in Oklahoma-Region 2 results in the linear regression given in Equation 10.

$$W = 15.74 * DA^{0.333} \quad \text{(Eq. 10)}$$

The coefficient of determination (R^2) for Equation 10 was determined to be 0.83, as shown in Figure 10.

Figure 11 shows a plot of mean bankfull depth versus drainage area. Again, four sets of data are plotted on this graph, Oklahoma-Region 1, Oklahoma-Region 2, Texas and NRCS. Equation 11 gives the linear regression of all the data:

$$H = 2.81 * DA^{0.073} \qquad \text{(Eq. 11)}$$

where H is the mean bankfull depth in feet and DA is the drainage area in square miles. The coefficient of determination (R^2) for this relationship was determined to be 0.10 as shown in Figure 11. Removing the data points in Oklahoma-Region 2 results in the linear regression given in Equation 12.

$$H = 2.76 * DA^{0.089} \qquad \text{(Eq. 12)}$$

The coefficient of determination (R^2) for Equation 12 was determined to be 0.18, as shown in Figure 11. The R^2 value for the mean bankfull depth versus drainage area data is the lowest value observed, indicating more scatter in the data. This is consistent with Rosgen's findings (from personal conversations).

In addition to developing relationships between bankfull discharge and channel dimensions as a function of drainage area, this study also evaluated potential relationships between bankfull discharge and bankfull cross-sectional area. Figure 12 shows a plot of bankfull discharge versus bankfull cross-sectional area. As with the other plots, four sets of data are plotted on this graph, Oklahoma-Region 1, Oklahoma-Region 2, Texas and NRCS. Equation 13 gives the linear regression of all the data:

$$Q = 2.79 * A^{1.068} \qquad \text{(Eq. 13)}$$

where Q is the bankfull discharge in cubic feet per second and A is the bankfull cross-sectional area in square feet. The coefficient of determination (R^2) for this relationship was determined to be 0.82 as shown in Figure 12. Removing the data points in Oklahoma-Region 2 results in the linear regression given in Equation 14.

$$Q = 4.90 * A^{0.997} \qquad \text{(Eq. 14)}$$

The coefficient of determination (R^2) for Equation 14 was determined to be 0.87, as shown in Figure 12.

The regression equations presented above, specifically Equations 6, 8, 10 and 14 have coefficients of determination (R^2) values of 0.80, 0.77, 0.83 and 0.87, respectively, which are considered good to very good. However, in order to see if this may be improved upon, the data was sorted and analyzed by stream type, river basin, climate zone, mean annual precipitation and ecoregion.

5.3.2. Stream Type

An evaluation of the data by stream type was examined first. The data set presented in Tables 2 and 3 was sorted by stream type and re-evaluated. The data from Oklahoma-Region 2 was excluded from this phase of the study since it departed from the norm. The NRCS data was not included because the stream types of the sites surveyed were unknown.

Plots of bankfull discharge, bankfull cross-sectional area, bankfull width and bankfull mean depth versus drainage area, sorted by stream type are shown in Figures 13 to 16, respectively. A plot of bankfull discharge versus bankfull cross-sectional area by stream type is shown in Figure 17. Regressions were determined for five major stream types (B, C, E, F and G) and three sub-stream types (C4, C5 and C5c-). The limited number of certain stream types precluded a more detailed analysis.

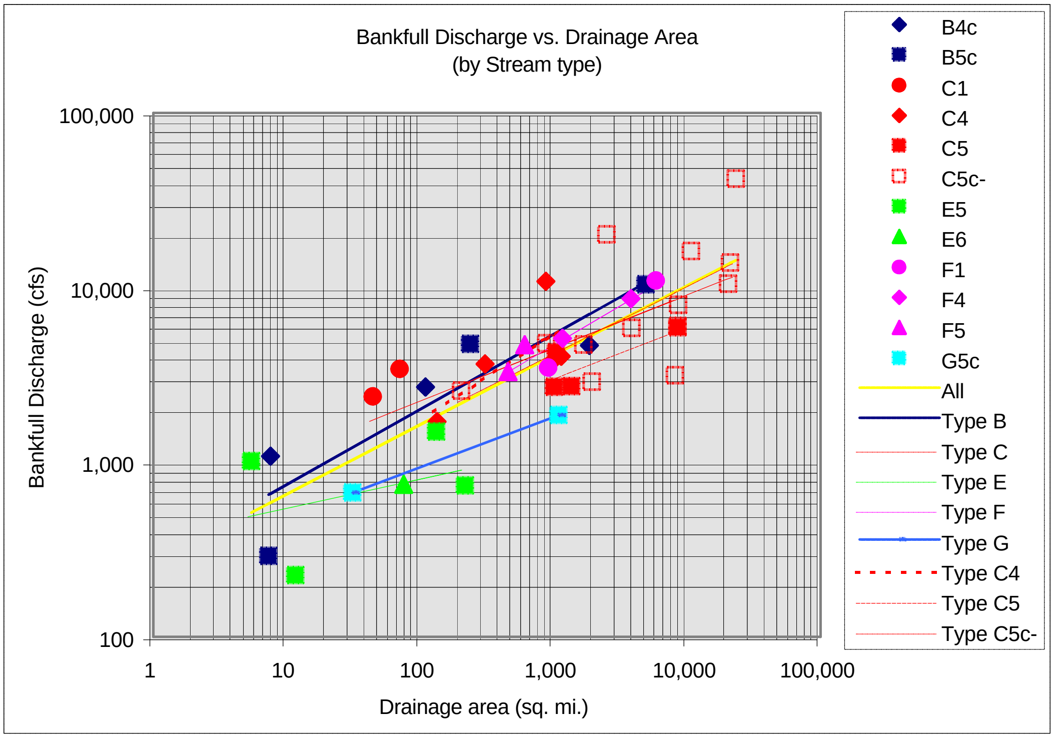

Figure 13: Plot of Bankfull Discharge (cfs) versus Drainage Area (mi^2) – By Stream Type.

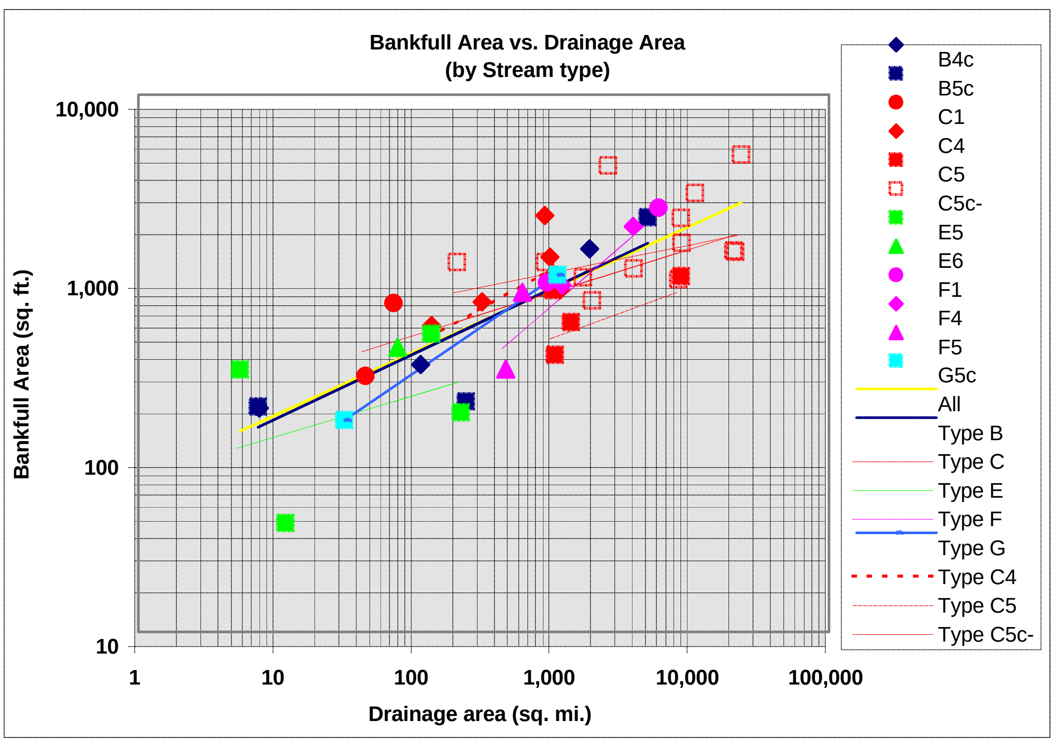

Figure 14: Plot of Bankfull Cross-sectional Area versus Drainage Area – By Stream Type.

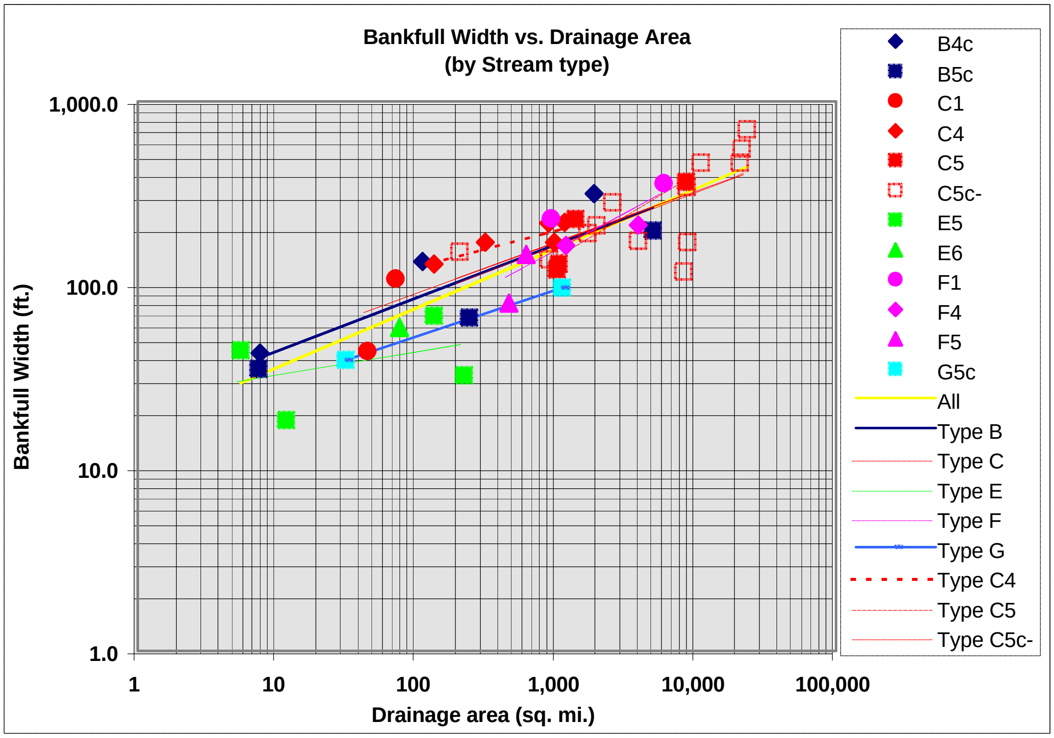

Figure 15: Plot of Bankfull Width (ft) versus Drainage Area (mi^2) – By Stream Type.

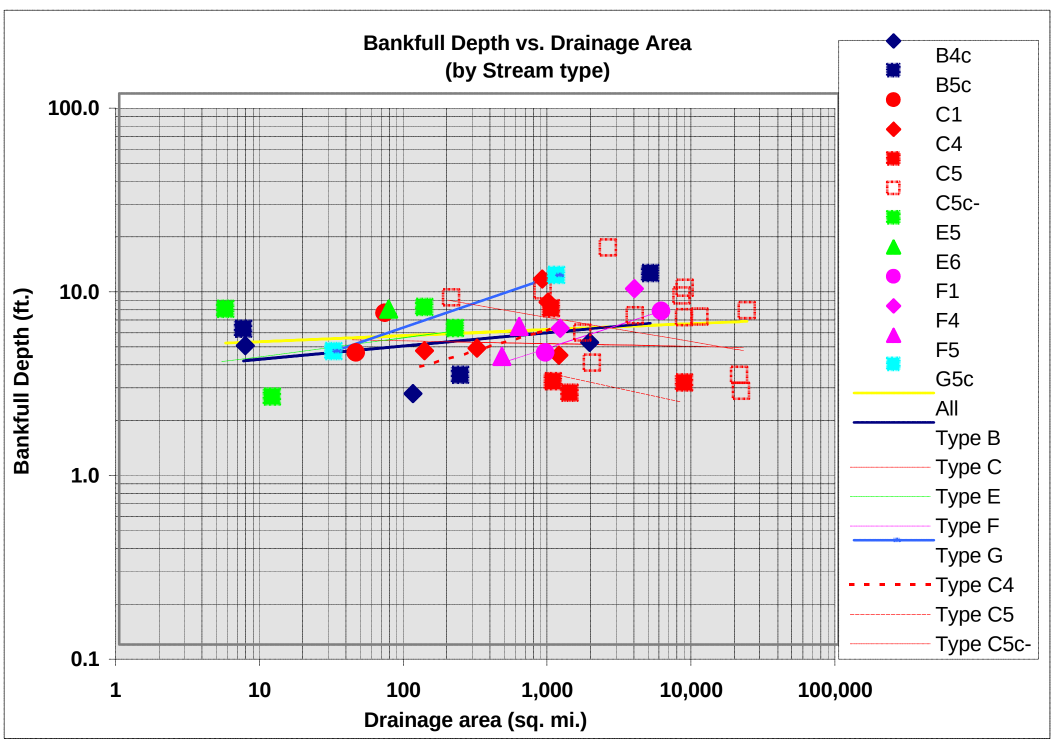

Figure 16: Plot of Bankfull Depth (ft) versus Drainage Area (mi^2) – By Stream Type.

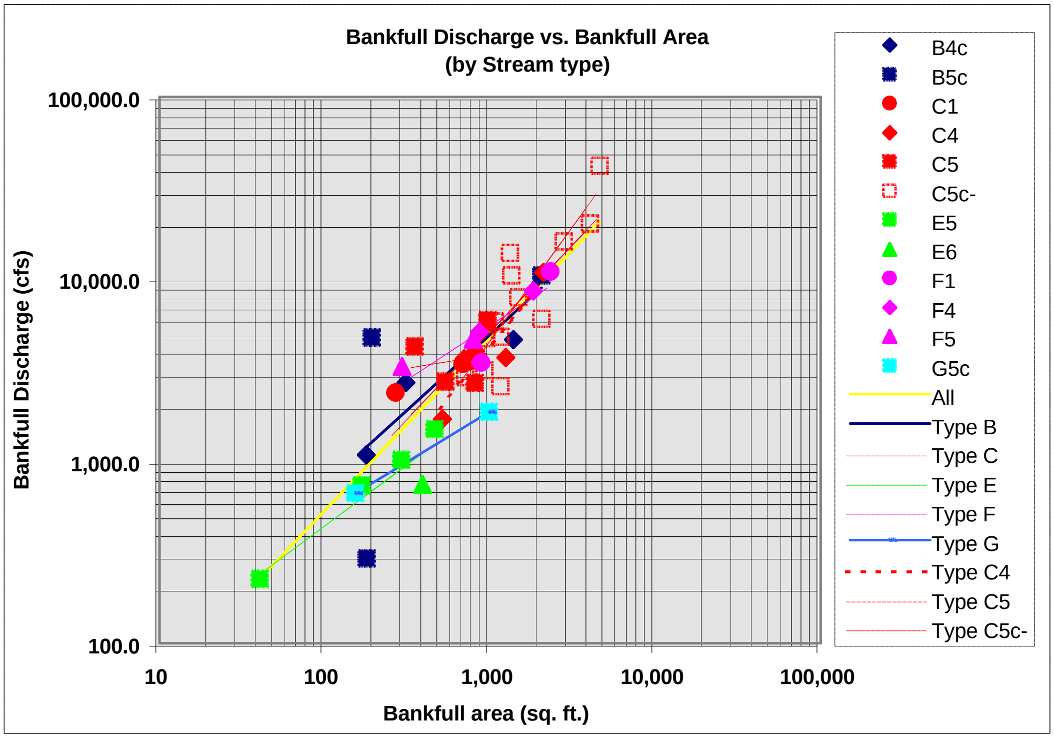

Figure 17: Plot of Bankfull Discharge versus Cross-sectional Area – By Stream Type.

Tables 4 to 8 show the regression equations determined by stream type for the bankfull discharge versus drainage area, the bankfull cross-sectional area versus drainage area, the bankfull width versus drainage area, the bankfull mean depth versus drainage area and the bankfull discharge versus bankfull cross-sectional area, respectively. The coefficients of determination (R^2) and sample size (n) are also provided. Regression equations are not provided for stream types with a sample size less than five.

Referring to Figure 13 and Table 4, it can be seen that for the most part, sorting the data by stream type only seems to increase the scatter of the data and thus lower the coefficients of determination (R^2), although some stream types have better relationships than others do. The same can be said for the remaining data presented in Figures 14 to 17 and Tables 5 to 8. Once again, the best correlation of the data was found on the bankfull discharge versus bankfull cross-sectional area plots, as can be seen in Figure 17 and Table 8.

Table 4: Regression Equations for Bankfull Discharge versus Drainage Area – by Stream Type.

Stream Type	Equation	R^2	n
B	Q=277.30*DA^0.430	0.83	6
C	Q=566.79*DA^0.303	0.48	24
E	Q=382.77*DA^0.167	0.14	5
F	Q=212.95*DA^0.448	0.89	6
C4	Q=176.11*DA^0.498	0.48	5
C5c-	Q=297.63*DA^0.385	0.42	13
All	Q=262.53*DA^0.398	0.70	43

Table 5: Regression Equations for Bankfull Area versus Drainage Area – by Stream Type.

Stream Type	Equation	R^2	n
B	A=67.34*DA^0.363	0.80	6
C	A=177.68*DA^0.241	0.39	24
E	A=86.34*DA^0.230	0.14	5
F	A=7.98*DA^0.662	0.86	6
C4	A=63.67*DA^0.431	0.52	5
C5c-	A=408.67*DA^0.157	0.15	13
All	A=72.70*DA^0.352	0.65	43

Table 6: Regression Equations for Bankfull Width versus Drainage Area – by Stream Type.

Stream Type	Equation	R^2	n
B	W=22.15*DA^0.292	0.81	6
C	W=25.30*DA^0.279	0.65	24
E	W=24.76*DA^0.126	0.15	5
F	W=9.21*DA^0.690	0.69	6
C4	W=49.85*DA^0.203	0.76	5
C5c-	W=22.44*DA^0.290	0.48	13
All	W=16.70*DA^0.325	0.76	43

Table 7: Regression Equations for Bankfull Depth versus Drainage Area – by Stream Type.

Stream Type	Equation	R^2	n
B	H=3.04*DA^0.072	0.14	6
C	H=5.80*DA^-0.015	0.003	24
E	H=3.49*DA^0.104	0.12	5
F	H=0.87*DA^0.252	0.65	6
C4	H=1.28*DA^0.228	0.24	5
C5c-	H=18.21*DA^-0.133	0.14	13
All	H=4.14*DA^0.326	0.02	43

Table 8: Regression Equations for Bankfull Discharge versus Bankfull Area – by Stream Type.

Stream Type	Equation	R^2	n
B	Q=16.44*A^0.826	0.51	6
C	Q=6.88*A^0.956	0.71	24
E	Q=19.46*A^0.677	0.88	5
F	Q=93.90*A^0.592	0.79	6
C4	Q=2.05*A^1.105	0.84	5
C5c-	Q=0.55*A^1.30	0.76	13
All	Q=6.60*A^0.954	0.76	43

5.3.3. River (Planning) Basin

The relationship of the data as related to various hydro-geographic provinces of the state was then analyzed. Provinces, or regions, were selected based on several different factors including river basin, climate zone, mean annual precipitation and ecoregion. The river basins selected for this analysis were the planning basins, as reported in the State of Oklahoma Water Quality Assessment Report (1992). There are 11 major river (planning) basins in Oklahoma; the Cimarron, the upper Arkansas, the lower Arkansas, the upper Canadian, the lower Canadian, the upper North Canadian, the lower North Canadian, the Grand Neosho, the Washita, the upper Red and the lower Red. Figure 18 shows the locations of the major river basins in the state in relation to the geomorphic survey sites. Due to the limited number of sites in the database, it was necessary to combine some of the river basins for the analysis. The upper and lower Canadian River basins were combined into one basin, the Canadian River basin. Similarly, the upper and lower North Canadian River basins, the upper and lower Arkansas River basins and the upper and lower Red River basins were combined into the North Canadian River basin, the Arkansas River basin and the Red River Basin, respectively.

The data was sorted according to the river basin in which the geomorphic survey site was located and then reanalyzed. The NRCS and Texas data was omitted from this analysis. Figures 19 to 22 show plots of bankfull discharge, bankfull cross-sectional area, bankfull width, and bankfull depth versus drainage area, respectively, sorted by river basin. A plot of bankfull discharge versus bankfull cross-sectional area sorted by river basin is shown in Figure 23. The coefficients of determination (R^2) for each regression line are provided.

Tables 9 to 13 show the regression equations determined by river basin for the bankfull discharge versus drainage area, the bankfull cross-sectional area versus drainage area, the bankfull width versus drainage area, the bankfull mean depth versus drainage area and the bankfull discharge versus bankfull cross-sectional area, respectively. Since the Texas data was omitted, only 45 sites were included in this analysis. The coefficients of determination (R^2) and sample size (n) are also given.

It can be seen in Figures 19 to 23 and Tables 9 to 13 that the five sites referred to above as Oklahoma-Region 2 significantly impacted the results presented here. Three of the sites are located in the North Canadian basin, one is located in the Cimarron River basin and one is in the Washita River basin. The coefficients of determination (R^2) of the regression lines through the data from the Arkansas, Canadian, and Grand Neosho basins are typically the highest, indicating that the given equations better fit the data than do the equations given for the North Canadian, Cimarron and Washita River basins.

The best (highest R^2) relationships were typically observed in the plots of bankfull discharge versus bankfull cross-sectional area, bankfull width versus drainage area and bankfull cross-sectional area versus drainage area. The lowest R^2 relationships were typically observed in the plots of bankfull depth versus drainage area.

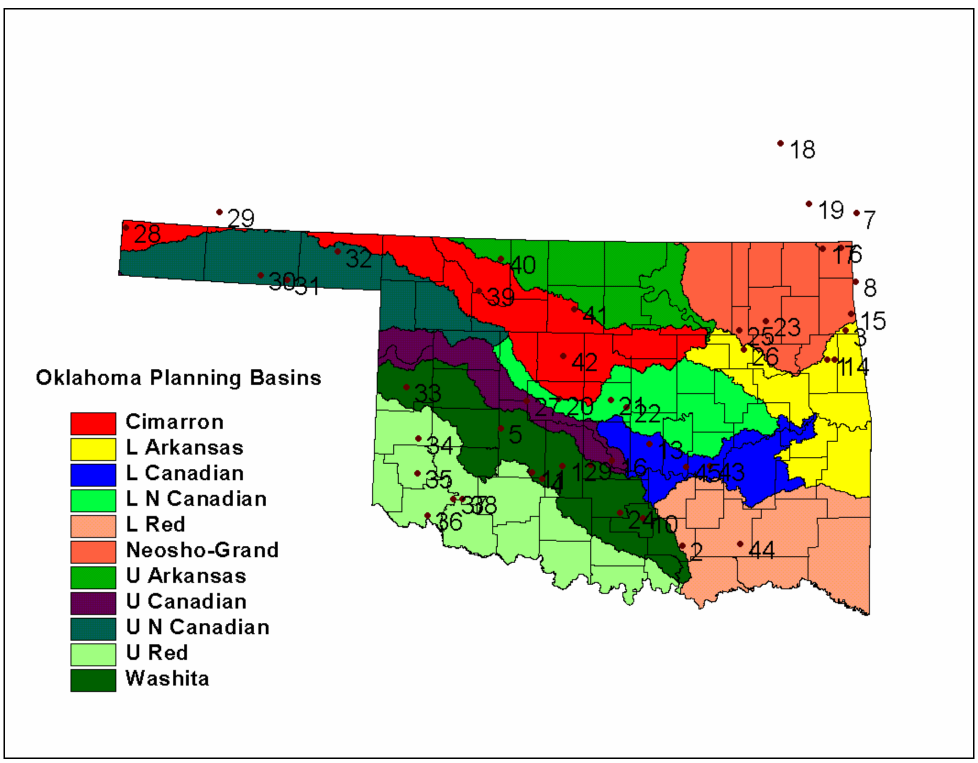

Figure 18: Locations of Oklahoma's river (planning) basins.

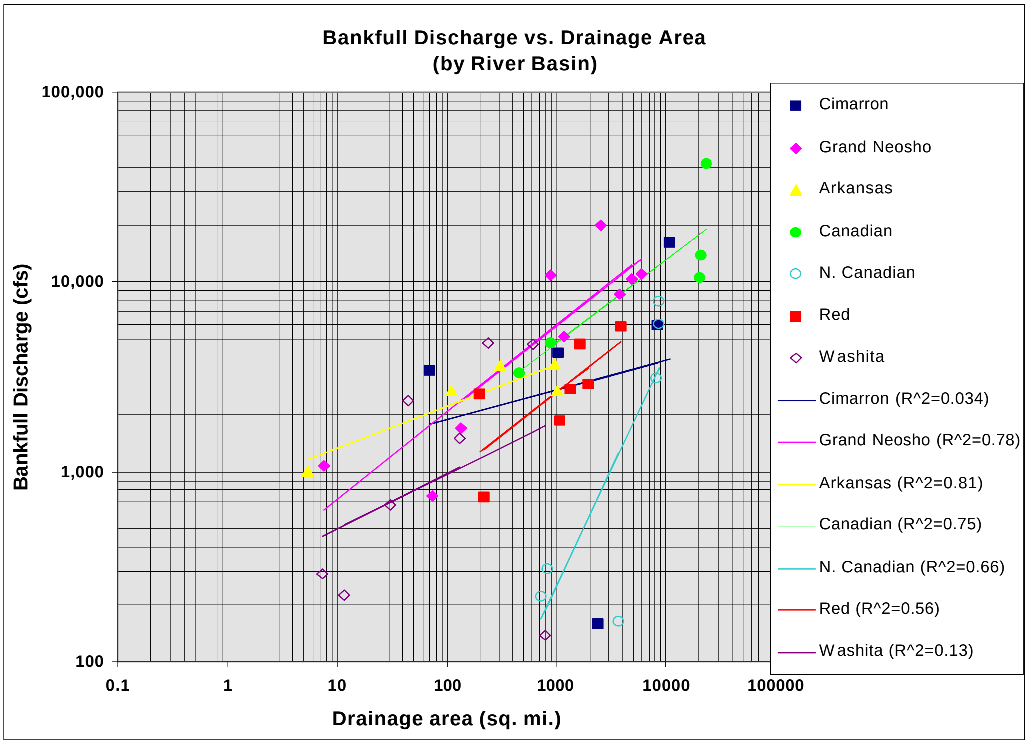

Figure 19: Plot of Bankfull Discharge versus Drainage Area – By River Basin.

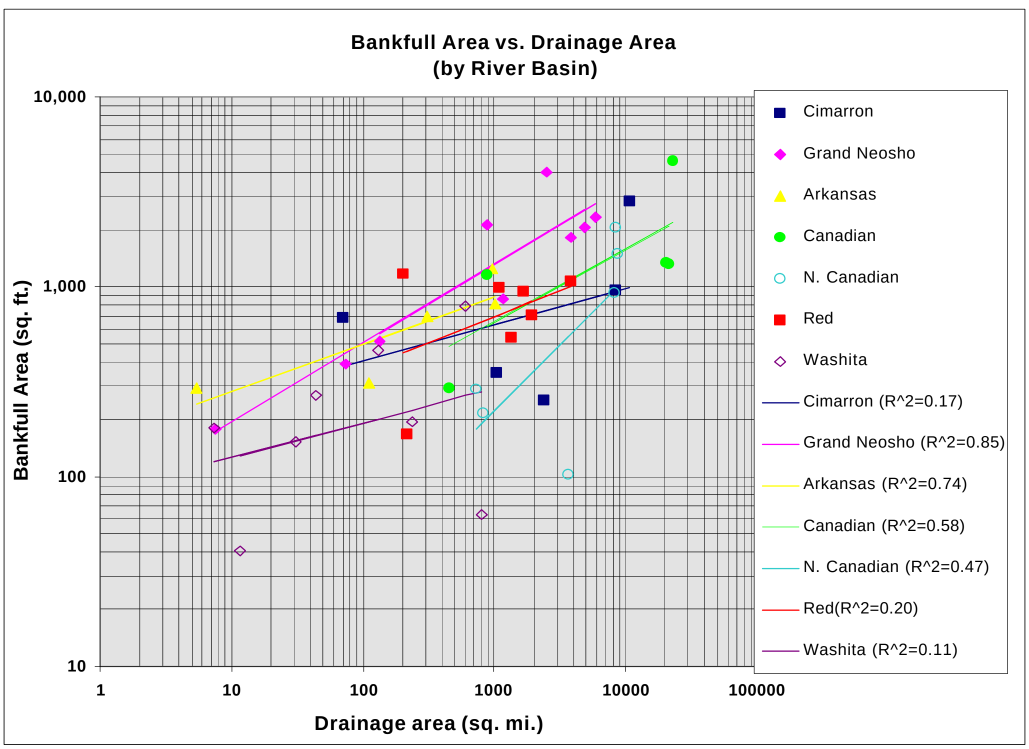

Figure 20: Plot of Bankfull Area versus Drainage Area – By River Basin.

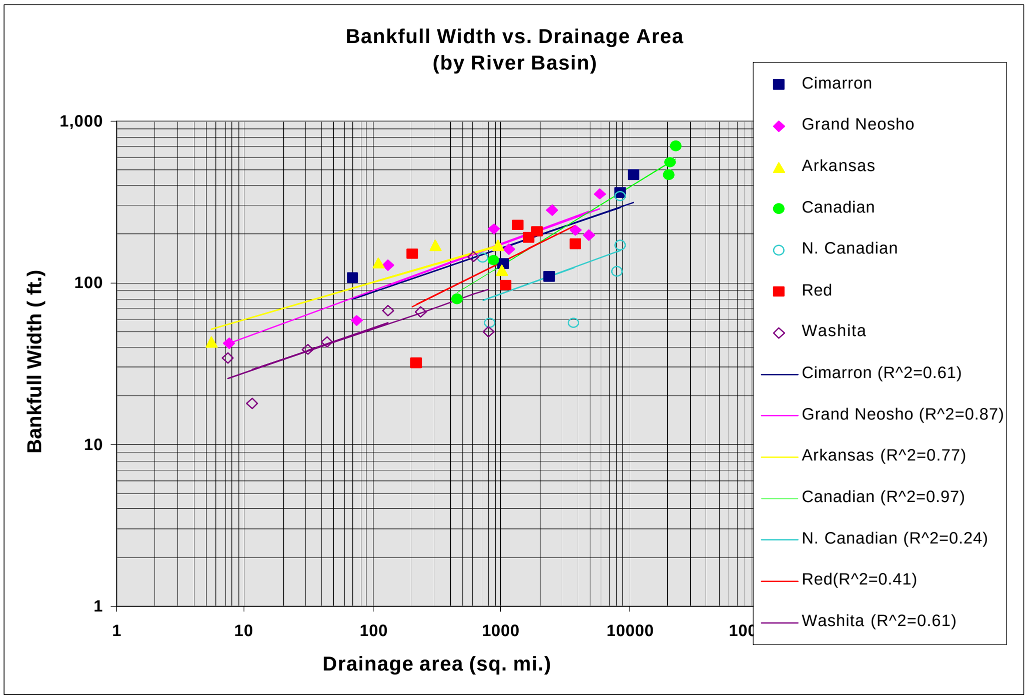

Figure 21: Plot of Bankfull Width versus Drainage Area – By River Basin.

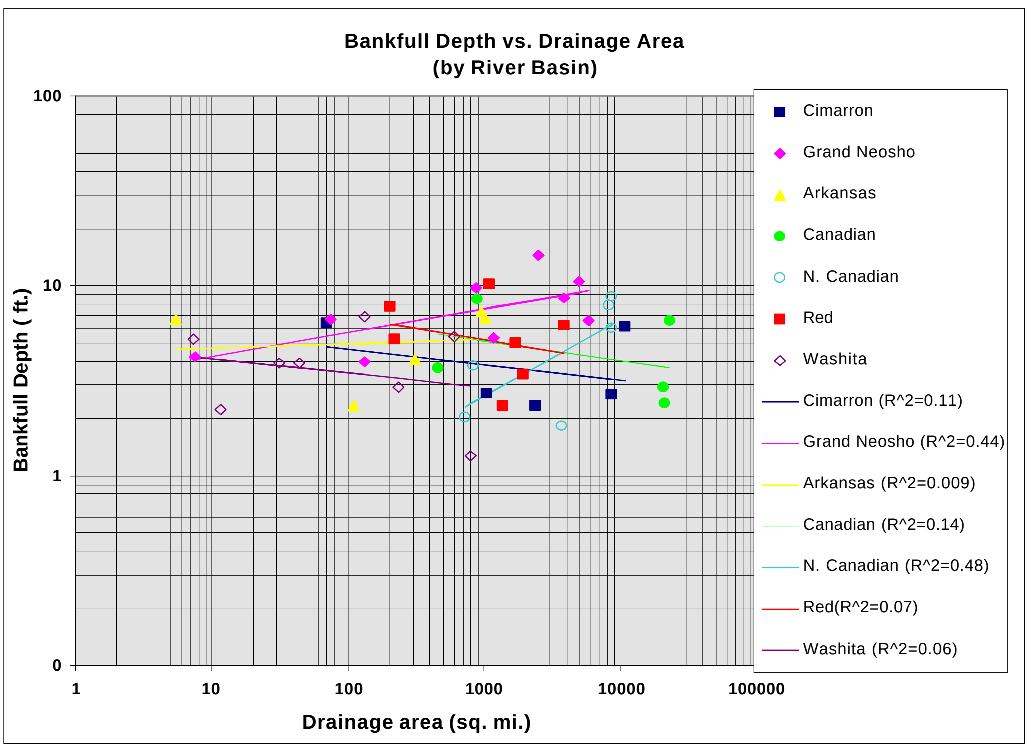

Figure 22: Plot of Bankfull Depth versus Drainage Area – By River Basin.

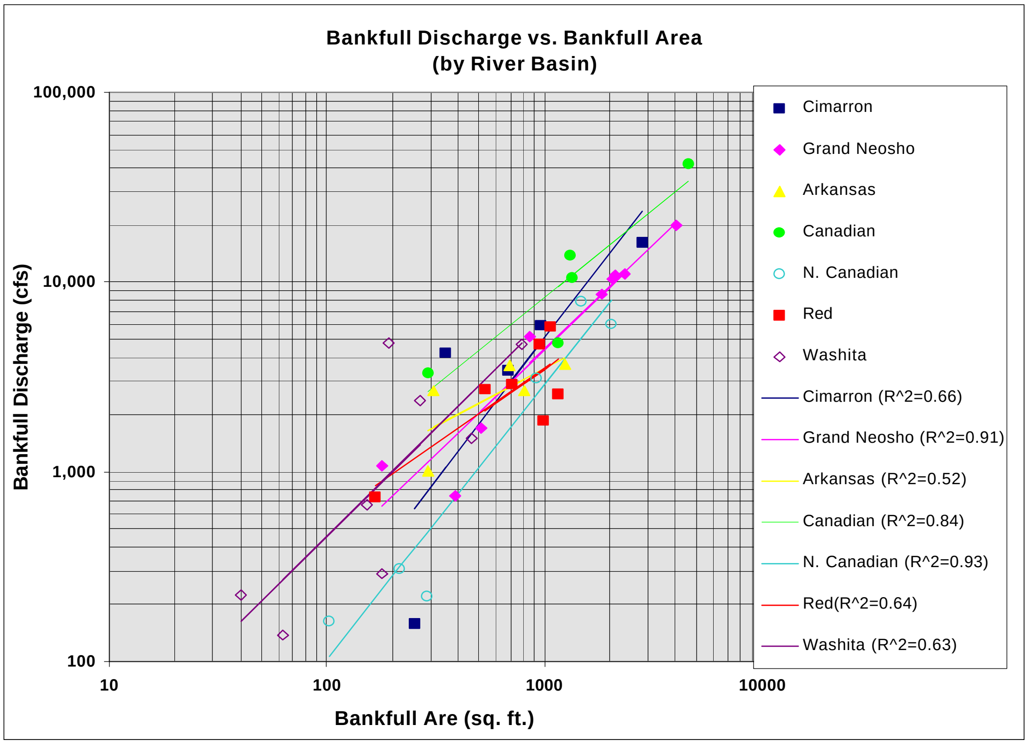

Figure 23: Plot of Bankfull Discharge versus Bankfull Area – By River Basin.

Table 9: Regression Equations for Bankfull Discharge versus Drainage Area – By River Basin.

River Basin	Equation	R^2	n
Cimarron	Q=913.67*DA^0.157	0.03	5
Grand Neosho	Q=249.91*DA^0.458	0.78	9
Arkansas	Q=793.48*DA^0.222	0.81	5
Canadian	Q=229.29*DA^0.440	0.75	5
N. Canadian	Q=0.051*DA^1.229	0.66	6
Red	Q=113.84*DA^0.454	0.56	7
Washita	Q=259.04*DA^0.287	0.13	8
All	Q=259.47*DA^.347	0.30	45

Table 10: Regression Equations for Bankfull Area versus Drainage Area – By River Basin

River Basin	Equation	R^2	n
Cimarron	A=169.06*DA^0.190	0.17	5
Grand Neosho	A=74.34*DA^0.415	0.85	9
Arkansas	A=156.40*DA^0.251	0.74	5
Canadian	A=45.98*DA^0.383	0.58	5
N. Canadian	A=1.85*DA^0.693	0.47	6
Red	A=104.25*DA^0.274	0.20	7
Washita	A=82.71*DA^0.182	0.11	8
All	A=72.85*DA^0.321	0.43	45

Table 11: Regression Equations for Bankfull Width versus Drainage Area – By River Basin

River Basin	Equation	R^2	n
Cimarron	W=25.18*DA^0.271	0.61	5
Grand Neosho	W=23.46*DA^0.289	0.87	9
Arkansas	W=34.98*DA^0.230	0.77	5
Canadian	W=4.45*DA^0.486	0.97	5
N. Canadian	W=11.43*DA^0.291	0.24	6
Red	W=8.75*DA^0.395	0.41	7
Washita	W=15.10*DA^0.269	0.61	8
All	W=16.82*DA^0.306	0.66	45

Table 12: Regression Equations for Bankfull Depth versus Drainage Area – By River Basin.

River Basin	Equation	R^2	n
Cimarron	H=6.71*DA^-0.082	0.11	5
Grand Neosho	H=3.17*DA^0.125	0.44	9
Arkansas	H=4.47*DA^0.022	0.009	5
Canadian	H=10.36*DA^-0.103	0.14	5
N. Canadian	H=0.16*DA^0.403	0.48	6
Red	H=11.91*DA^-0.121	0.07	7
Washita	H=4.89*DA^-0.074	0.06	8
All	H=4.12*DA^0.021	0.007	45

Table 13: Regression Equations for Bankfull Discharge versus Bankfull Area – By River Basin.

River Basin	Equation	R^2	n
Cimarron	Q=0.17*A^1.494	0.66	5
Grand Neosho	Q=2.15*A^1.103	0.91	9
Arkansas	Q=52.17*A^0.609	0.52	5
Canadian	Q=13.55*A^0.927	0.84	5
N. Canadian	Q=0.14*A^1.438	0.93	6
Red	Q=14.19*A^0.796	0.64	7
Washita	Q=2.36*A^1.142	0.63	8
All	Q=1.81*A^1.132	0.76	45

5.3.4. Climate Zone

The next analysis was the relationship of the data as related to various climate zones across the state. The climate zones selected for this analysis were developed by the National Climatic Data Center. There are nine climate zones in Oklahoma; the Central, the East Central, the West Central, the North Central, the South Central, the Northeast, the Southeast, the Southwest and the Panhandle. Figure 24 shows the locations of the climate zones in the state in relation to the geomorphic survey sites.

Survey sites were located in only eight of the nine climate zones, as can be seen in Figure 24. No sites were located in the Southeast climate zone. Sites 7 and 8, the Spring River near Waco, Missouri and the Elk River near Tiff City, Missouri, respectively, and Sites 18 and 19, the Neosho River at Iola, Kansas and the Neosho River near Parsons, Kansas, respectively, were all assumed to be in the Northeast climate zone. Site 29, the Cimarron River near Elkhart, Kansas was assumed to be in the Panhandle climate zone. NRCS and Texas data were not used in this analysis, so only 45 sites were included in this analysis. Figures 25 to 28 show plots of bankfull discharge, bankfull cross-sectional area, bankfull width, and bankfull depth versus drainage area, respectively, sorted by climate zone. A plot of bankfull discharge versus cross-sectional area sorted by river basin is shown in Figure 29. The coefficients of determination (R^2) for each regression line are provided.

Tables 14 to 18 show the regression equations determined by climate zone for the bankfull discharge versus drainage area, the bankfull cross-sectional area versus drainage area, the bankfull width versus drainage area, the bankfull mean depth versus drainage area and the bankfull discharge versus bankfull cross-sectional area, respectively. The coefficients of determination (R^2) and sample size (n) are also given.

It can be seen in Figures 25 to 29 and Tables 14 to 18 that regression equations were only developed for four of the eight climate zones represented by the data. This is due to the fact that there weren't enough data points in the other climate zones for regressions to be meaningful. It may also be seen that the five sites referred to above as Oklahoma-

Region 2 once again significantly affected the results presented here. Four of the sites are located in the Panhandle climate zone and it may be observed that the plots for this climate zone do not follow the upward sloping trend one would expect, since discharge, and thus channel size, tends to increase with increasing drainage area.

The coefficients of determination (R^2) for the remaining climate zones, the Central, Northeast and Southwest, were good to excellent, with the exception of the bankfull discharge versus bankfull area relationship for the Central climate zone and the bankfull mean depth versus drainage area relationships in all climate zones.

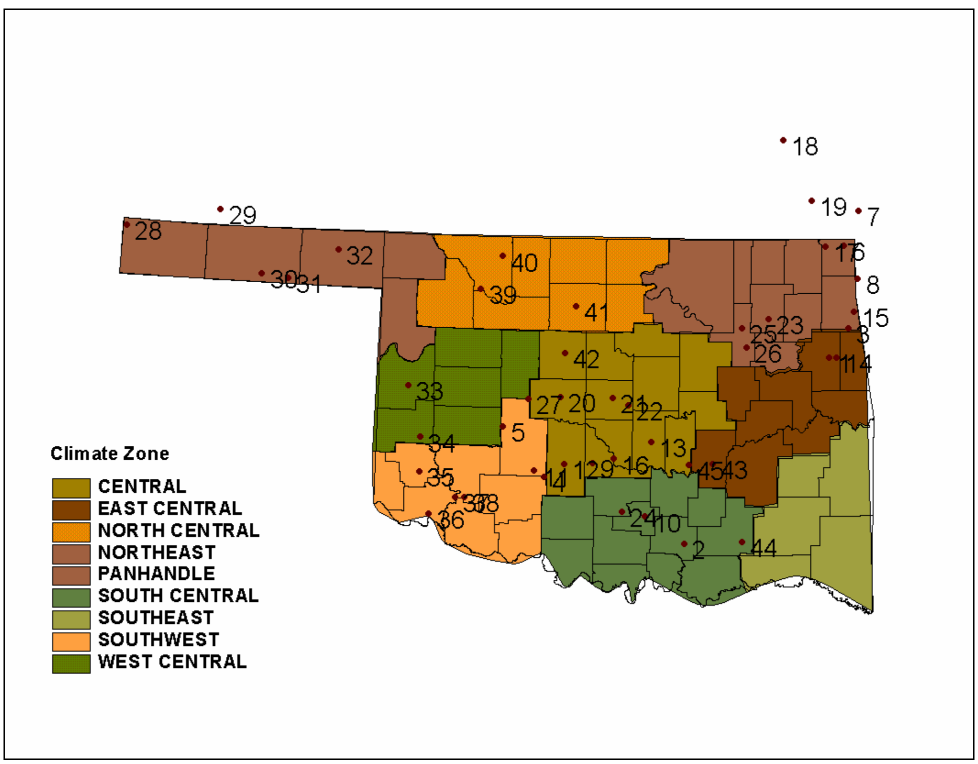

Figure 24: Locations of Oklahoma’s climate zones.

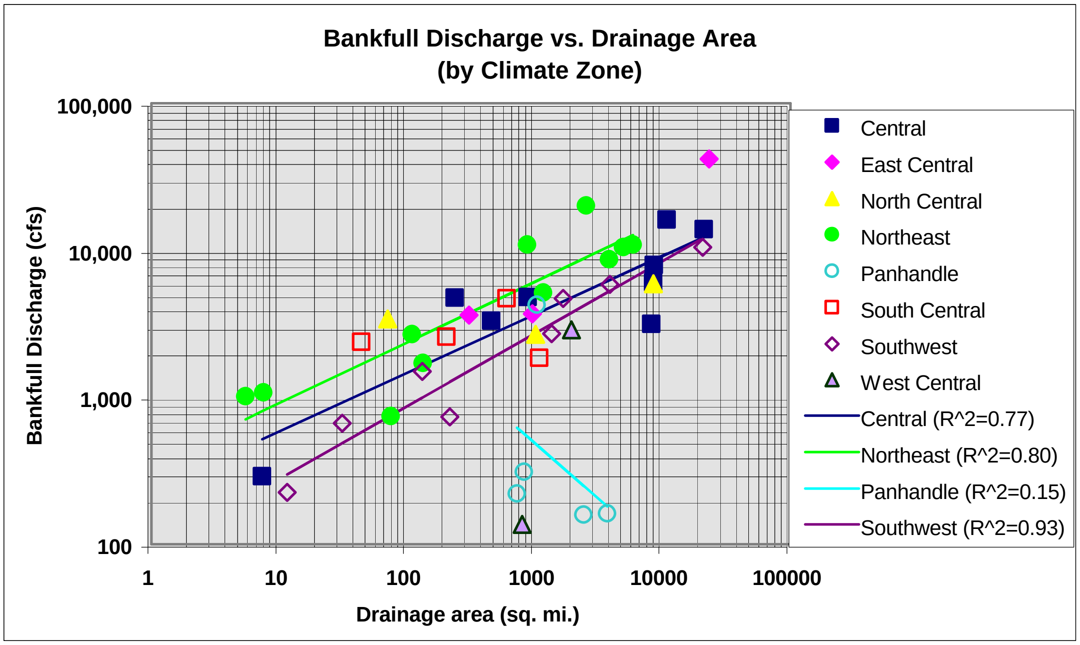

Figure 25: Plot of Bankfull Discharge versus Drainage Area – By Climate Zone.

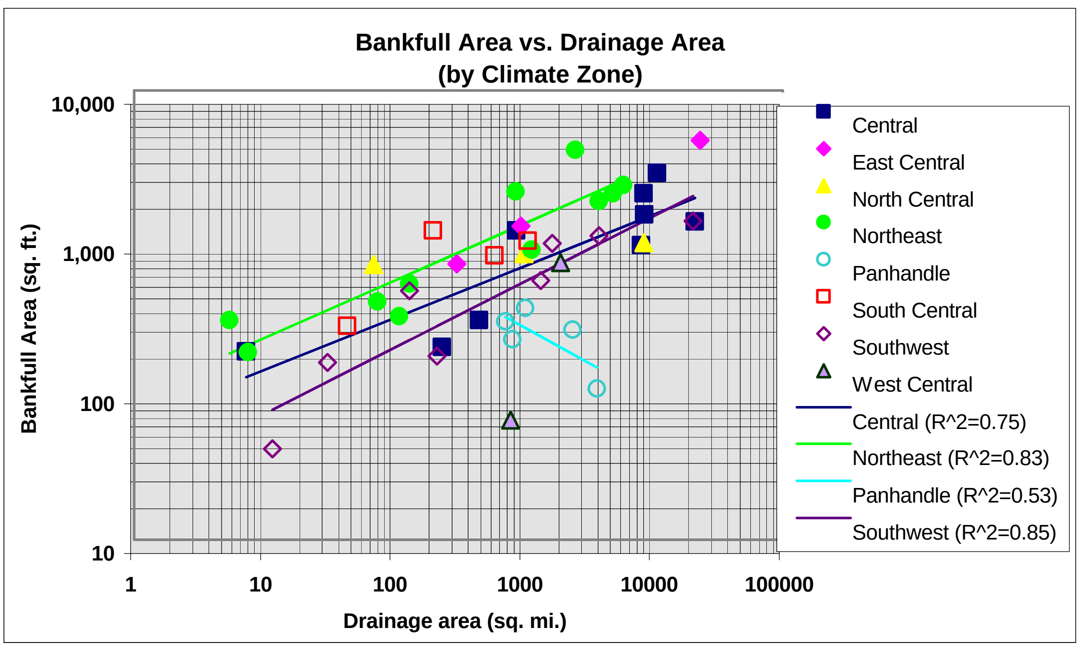

Figure 26: Plot of Bankfull Area versus Drainage Area – By Climate Zone.

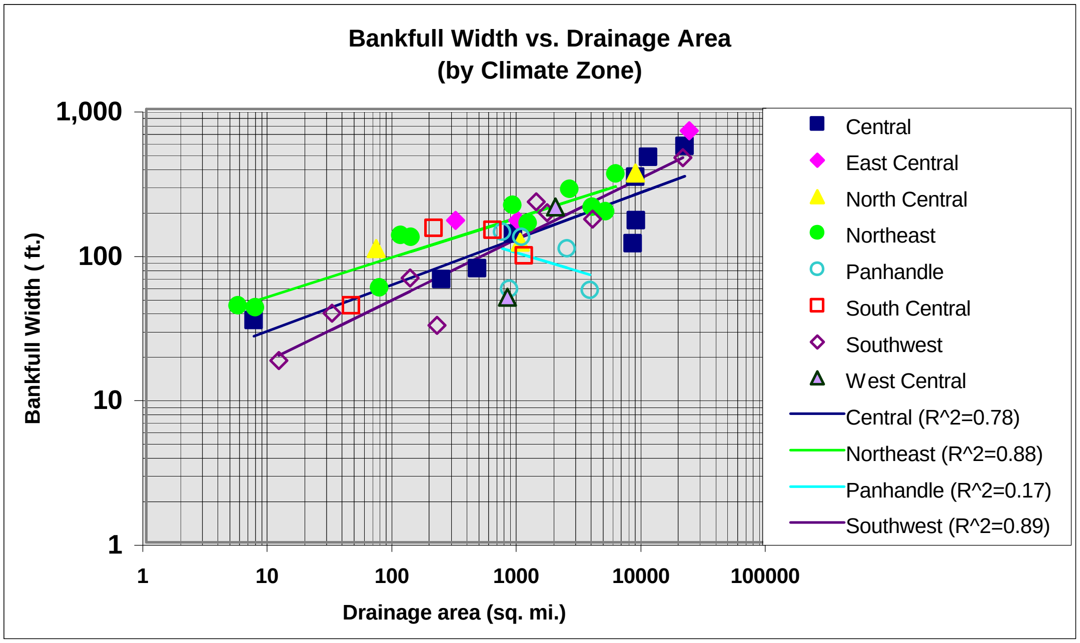

Figure 27: Plot of Bankfull Width versus Drainage Area – By Climate Zone.

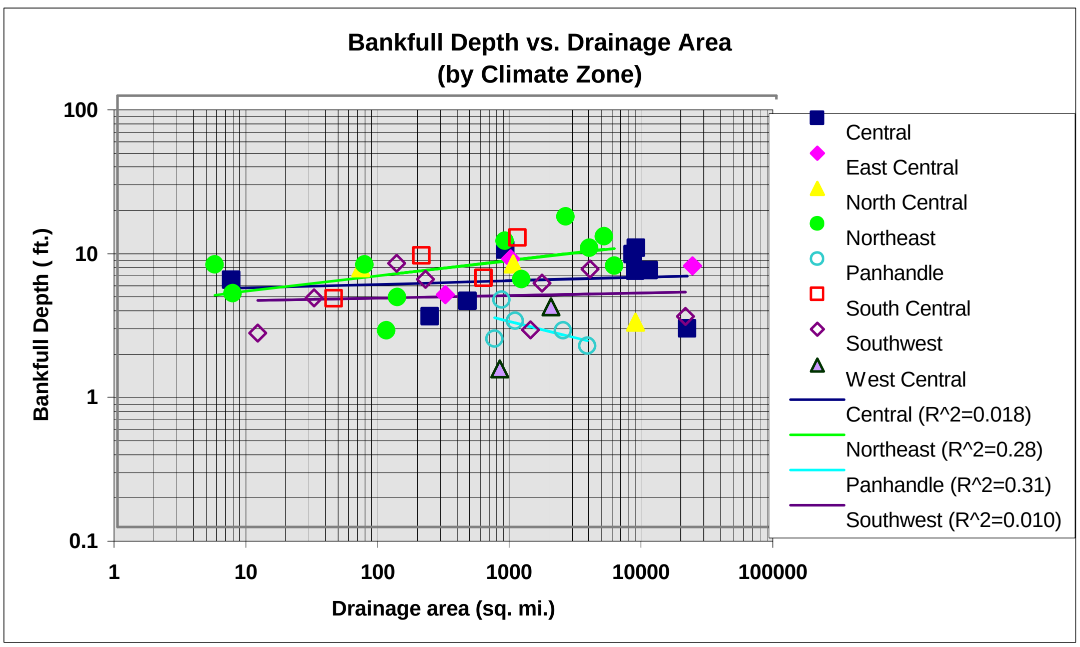

Figure 28: Plot of Bankfull Depth versus Drainage Area – By Climate Zone.

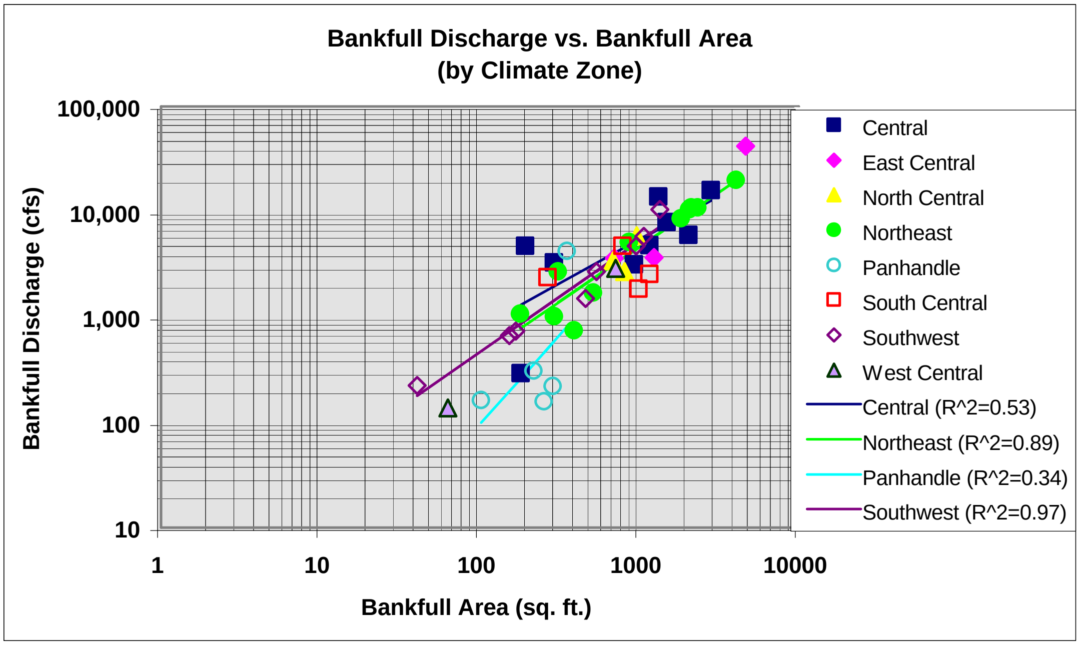

Figure 29: Plot of Bankfull Discharge versus Bankfull Area – By Climate Zone.

Table 14: Regression Equations for Bankfull Discharge versus Drainage Area – By Climate Zone.

Climate Zone	Equation	R^2	n
Central	Q=233.82*DA^0.398	0.77	9
Northeast	Q=351.83*DA^0.413	0.80	11
Panhandle	Q=95414.1*DA^-0.764	0.15	5
Southwest	Q=88.93*DA^0.495	0.93	8
All	Q=259.47*DA^.347	0.30	45

Table 15: Regression Equations for Bankfull Area versus Drainage Area – By Climate Zone.

Climate Zone	Equation	R^2	n
Central	A=61.39*DA^0.345	0.74	9
Northeast	A=91.86*DA^0.381	0.83	11
Panhandle	A=7403.53*DA^-0.482	0.53	5
Southwest	A=25.19*DA^0.439	0.85	8
All	A=72.85*DA^0.321	0.43	45

Table 16: Regression Equations for Bankfull Width versus Drainage Area – By Climate Zone.

Climate Zone	Equation	R^2	n
Central	W=14.11*DA^0.320	0.78	9
Northeast	W=26.91*DA^0.274	0.88	11
Panhandle	W=595.03*DA^-0.258	0.17	5
Southwest	W=6.96*DA^0.422	0.89	8
All	W=16.82*DA^0.306	0.66	45

Table 17: Regression Equations for Bankfull Depth versus Drainage Area – By Climate Zone.

Climate Zone	Equation	R^2	n
Central	H=4.35*DA^0.025	0.02	9
Northeast	H=3.41*DA^0.108	0.28	11
Panhandle	H=12.44*DA^-0.224	0.31	5
Southwest	H=3.61*DA^0.017	0.01	8
All	H=4.12*DA^0.021	0.007	45

Table 18: Regression Equations for Bankfull Discharge versus Bankfull Area – By Climate Zone.

Climate Zone	Equation	R^2	n
Central	Q=17.48*A^0.831	0.53	9
Northeast	Q=3.525*A^1.040	0.89	11
Panhandle	Q=0.04*A^1.693	0.34	5
Southwest	Q=3.59*A^1.055	0.97	8
All	Q=1.81*A^1.132	0.76	45

5.3.6. Mean Annual Precipitation

The effect of mean annual precipitation on channel characteristics was evaluated next. Figure 30 shows isopleths of mean annual precipitation in relation to the geomorphic survey sites. The geographic information system (GIS) data coverage, as obtained from USGS, was subdivided into categories of 10 – 22 inches, 23 – 33 inches, 34 – 43 inches, 44 – 52 inches and 53 – 68 inches as shown in Figure 30. No sites were observed in the 53 – 68 inch zone, so only three of the four precipitation zones are represented by the data. Texas data was not included, but the NRCS data was, therefore 54 sites were included in this analysis.

Figures 31 to 34 show plots of bankfull discharge, bankfull cross-sectional area, bankfull width, and bankfull mean depth versus bankfull drainage area, respectively, sorted by mean annual precipitation. A plot of bankfull discharge versus cross-sectional area sorted by mean annual precipitation is shown in Figure 35. The coefficients of determination (R^2) for each regression line are provided.

Tables 19 to 23 show the regression equations determined based on mean annual precipitation for the bankfull discharge versus drainage area, the bankfull cross-sectional area versus drainage area, the bankfull width versus drainage area, the bankfull mean depth versus drainage area and the bankfull discharge versus bankfull cross-sectional area, respectively. The coefficients of determination (R^2) and sample size (n) are also given.

It can be seen in Figures 31 to 35 and Tables 19 to 23 that the five sites referred to above as Oklahoma-Region 2 once again significantly affected the results of the plots and the regression equations presented. Four of the five sites located in the area of the state with a mean annual precipitation of 10 – 22 inches are the sites previously identified as Oklahoma-Region 2. The plots for this precipitation zone reflect this in that the plots do not follow the upward sloping trend one would expect because, as stated above, the bankfull discharge and therefore the bankfull cross-sectional area tend to increase with increasing drainage area. Regression equations for the mean annual precipitation zone of 44 – 52 inches were not determined due to the fact that only four sites were located in this zone.

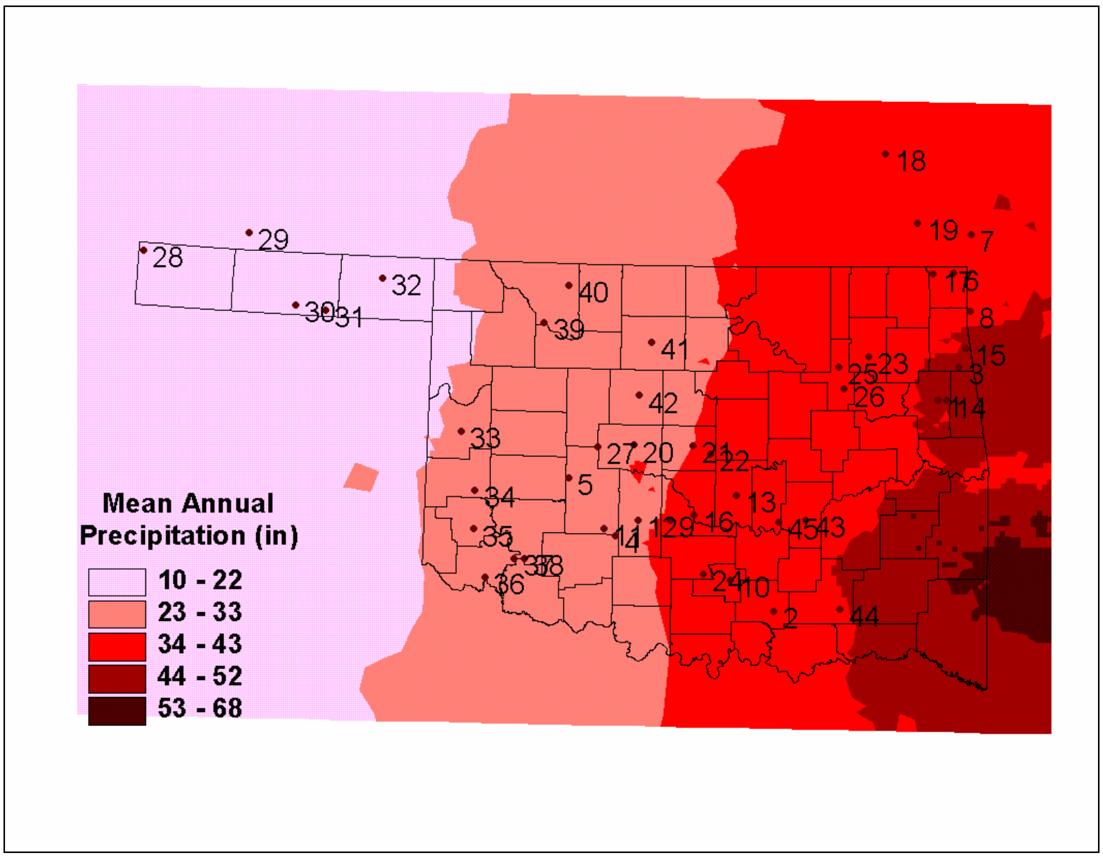

Figure 30: Mean Annual Precipitation Isopleths for Oklahoma.

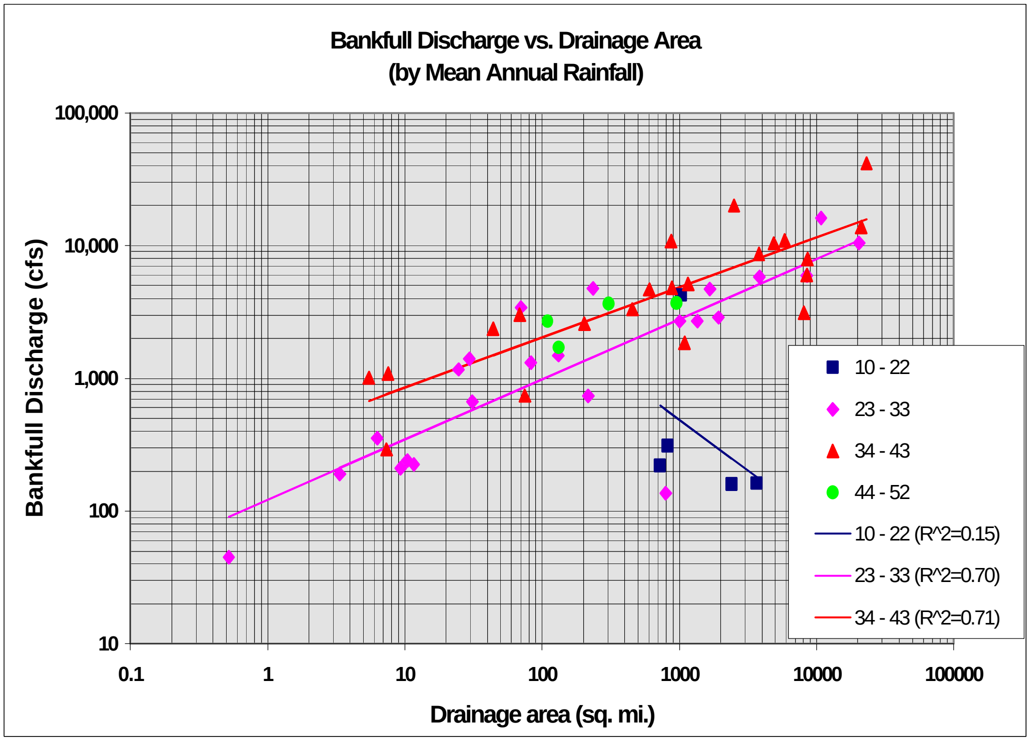

Figure 31: Plot of Bankfull Discharge versus Drainage Area – By Annual Precipitation.

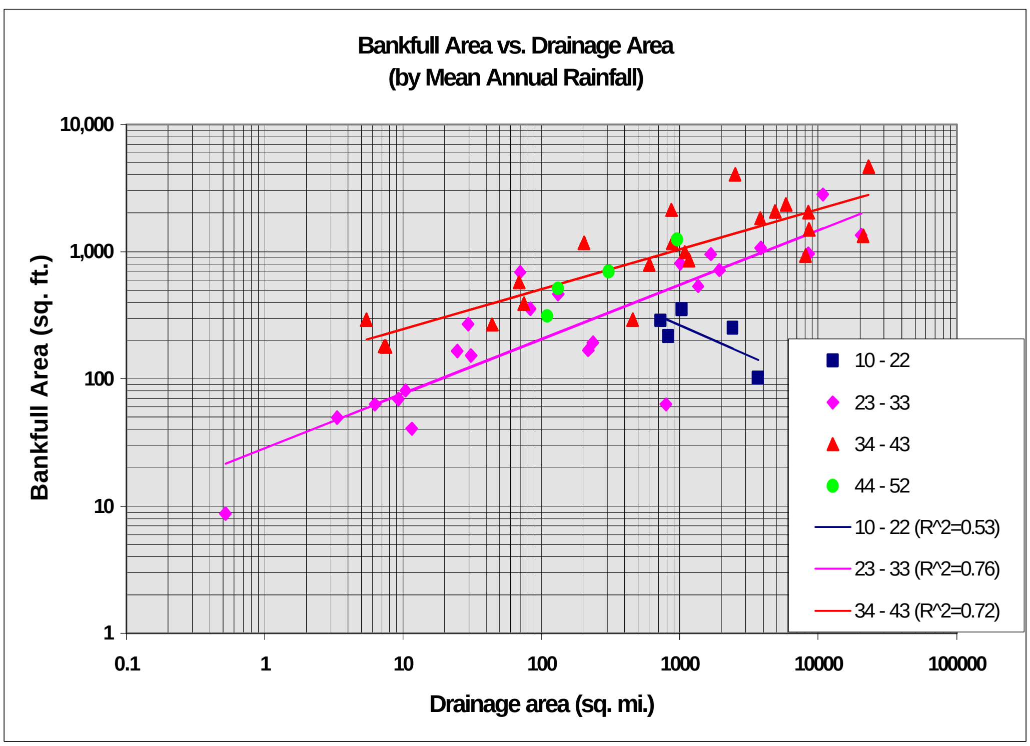

Figure 32: Plot of Bankfull Area versus Drainage Area – By Annual Precipitation.

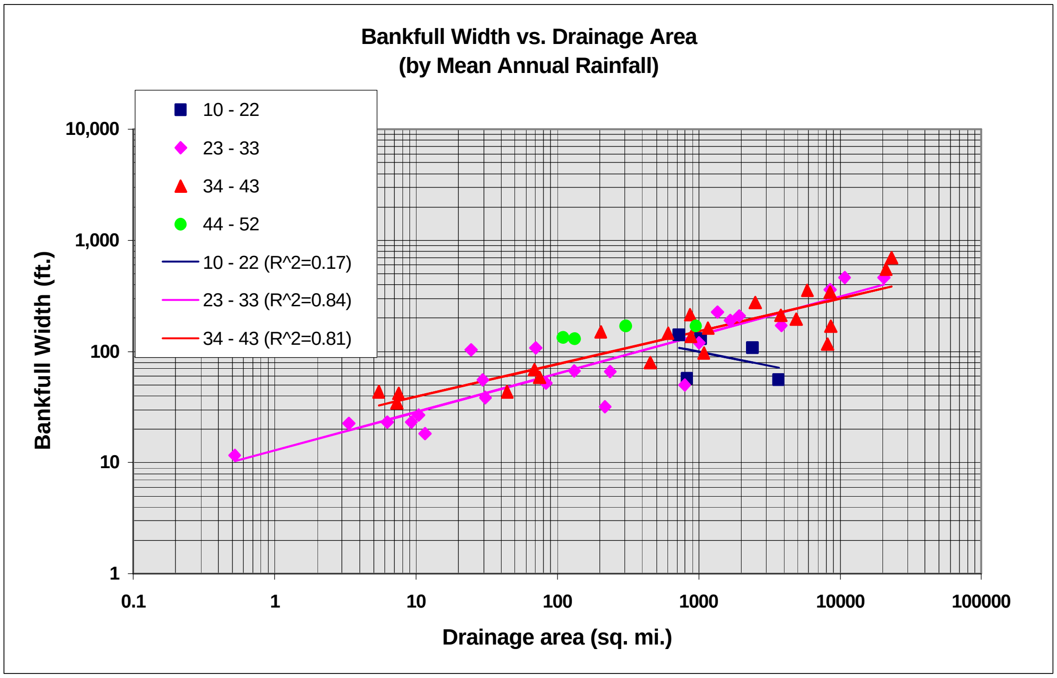

Figure 33: Plot of Bankfull Width versus Drainage Area – By Annual Precipitation.

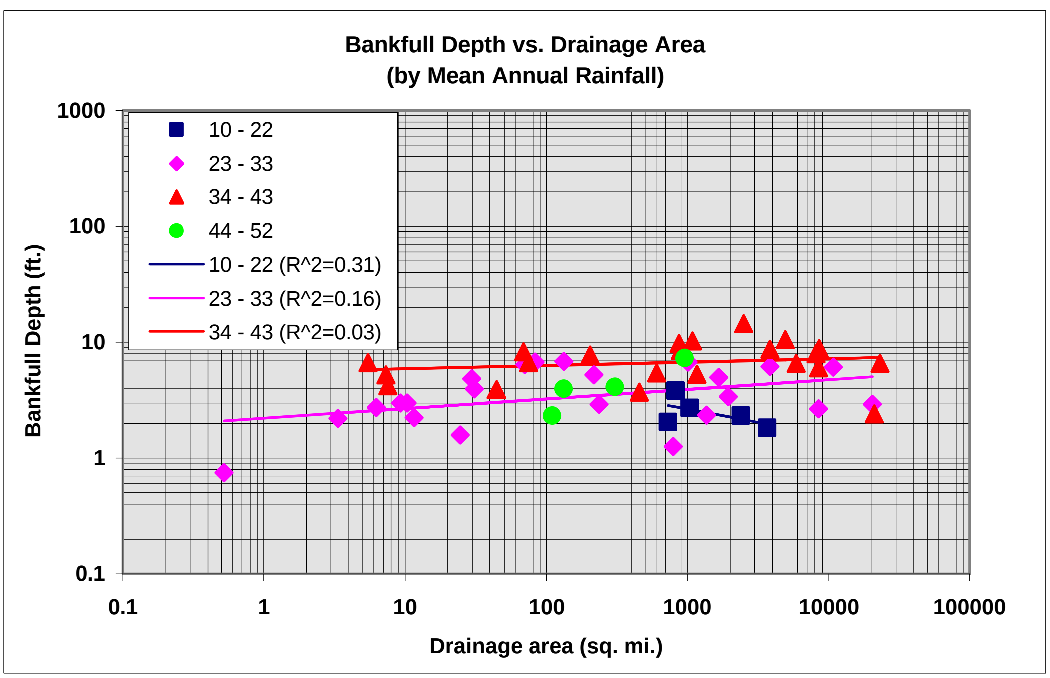

Figure 34: Plot of Bankfull Depth versus Drainage Area – By Annual Precipitation.

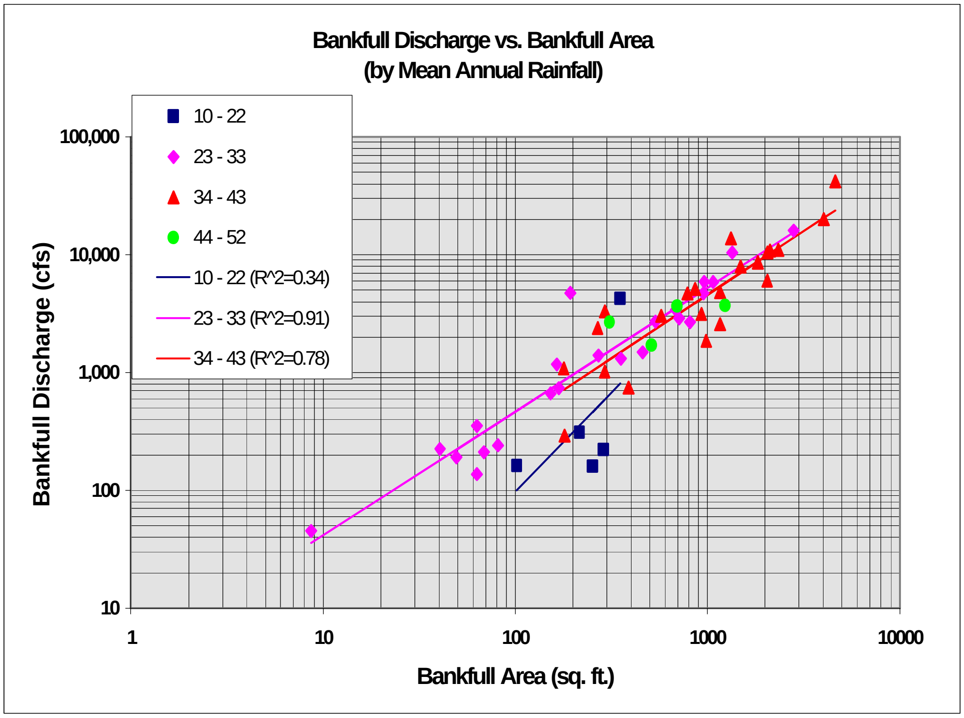

Figure 35: Plot of Bankfull Discharge versus Bankfull Area – By Annual Precipitation.

Table 19: Regression Equations for Bankfull Discharge versus Drainage Area – By Annual Precipitation.

Mean Precip.	Equation	R^2	n
10 - 22	Q=95414.1*DA^-0.764	0.15	5
23 - 33	Q=122.06*DA^0.453	0.70	23
34 - 43	Q=357.50*DA^0.378	0.71	22
All	Q=186.48*DA^0.395	0.46	54

Table 20: Regression Equations for Bankfull Area versus Drainage Area – By Annual Precipitation.

Mean Precip.	Equation	R^2	n
10 - 22	A=7403.53*DA^-0.483	0.53	5
23 - 33	A=28.51*DA^0.428	0.76	23
34 - 43	A=119.18*DA^0.314	0.72	22
All	A=46.60*DA^0.384	0.61	54

Table 21: Regression Equations for Bankfull Width versus Drainage Area – By Annual Precipitation.

Mean Precip.	Equation	R^2	n
10 - 22	W=595.03*DA^-0.258	0.17	5
23 - 33	W=12.89*DA^0.345	0.84	23
34 - 43	W=19.98*DA^0.294	0.81	22
All	W=16.18*DA^0.312	0.75	54

Table 22: Regression Equations for Bankfull Depth versus Drainage Area – By Annual Precipitation.

Mean Precip.	Equation	R^2	n
10 - 22	H=12.44*DA^-0.224	0.31	5
23 - 33	H=2.21*DA^0.082	0.16	23
34 - 43	H=5.51*DA^0.029	0.03	22
All	H=2.81*DA^0.074	0.11	54

Table 23: Regression Equations for Bankfull Discharge versus Bankfull Area – By Annual Precipitation.

Mean Precip.	Equation	R^2	n
10 - 22	Q=0.04*A^1.693	0.34	5
23 - 33	Q=3.64*A^1.053	0.91	23
34 - 43	Q=2.62*A^1.081	0.78	22
All	Q=2.73*A^1.073	0.82	54

It can be seen in Figures 31 to 35 and Tables 19 to 23 that the five sites referred to above as Oklahoma-Region 2 once again significantly affected the results of the plots and the regression equations presented. Four of the five sites located in the area of the state with a mean annual precipitation of 10 – 22 inches are the sites previously identified as Oklahoma-Region 2. The plots for this precipitation zone reflect this in that the plots do not follow the upward sloping trend one would expect because, as stated above, the bankfull discharge and therefore the bankfull cross-sectional area tend to increase with increasing drainage area. Regression equations for the mean annual precipitation zone of 44 – 52 inches were not determined due to the fact that only four sites were located in this zone.

The coefficients of determination (R^2) for the mean annual precipitation zones of 23 – 33 inches and 34 – 43 inches are good to excellent, using the criteria given previously, with the exception of the mean bankfull depth versus drainage area plots. A couple of points should be made concerning the mean bankfull depth versus drainage area plots for all of the regressions analyzed in this study. In addition to exhibiting poor coefficients of determination, the plots are also relatively flat. This is significant in that a flat line, with no slope, indicates that there is no correlation between bank full depth and drainage area; in other words because the bankfull depth is essentially the same regardless of the size of the drainage area. Thus, a significant finding of this study is that, for the sites surveyed, the bankfull mean depth is only slightly dependent on drainage area.

5.3.6. Ecoregion

Last, but certainly not least, the effect on channel characteristics as a function of ecoregion was evaluated. Figure 36 shows the Omernik (1987) ecoregions for the state in relation to the geomorphic survey sites. Ecoregions are delineated based on several factors including: the presence or absence of similar plant and animal communities, geology, climate, and precipitation/runoff patterns. For more information on ecoregion delineation refer to Omernik (1987). There are 11 ecoregions in Oklahoma; the Western High Plains, the Southwestern Tablelands, the Central Great Plains, the Flint Hills, the Central Oklahoma/Texas Plains, the South Central Plains, the Ouachita Mountains, the Arkansas Valley, the Boston Mountains, the Ozark Highlands and the Central Irregular Plains.

No sites were surveyed in the Flint Hills, the Arkansas Valley, the Ouachita Mountains or the South Central Plains. Thus, only 7 of the 11 ecoregions in the state are represented by the data. In addition, data for the Boston Mountains ecoregion and the Ozark Highlands ecoregion were combined into one region, the Boston Mountain/Ozark ecoregion. Similarly, data from the Southwestern Tablelands ecoregion and the Western High Plains ecoregion were combined into one region, the Southwest Tablelands/Western High Plains region. This was done due to the limited amount of data from these ecoregions and the similarity between them. Therefore, the data was divided into 5 ecoregions for this analysis. Regression equations were only developed for four of the five ecoregions because only four sites were observed to be in the Boston Mountain/Ozark ecoregion.

Site 7, the Spring River near Waco, Missouri and Sites 18 and 19, the Neosho River at Iola, Kansas and the Neosho River near Parsons, Kansas, respectively were found to be in the Central Irregular Plains ecoregion. Site 29, the Cimarron River near Elkhart, Kansas was found to be in the Western High Plains ecoregion. The Texas data, sites 46, 47 and 48 were determined to lie in the Central Great Plains ecoregion. Only nine of the ten NRCS sites were included in the analysis because one site, Whiskey Creek, did not have flow data available.

Figures 37 to 40 show plots of bankfull discharge, bankfull cross-sectional area, bankfull width, and bankfull mean depth versus drainage area, respectively, sorted by ecoregion. A plot of bankfull discharge versus bankfull cross-sectional area sorted by ecoregion is shown in Figure 41. The coefficients of determination (R^2) for each regression line are provided.

Tables 24 to 28 show the regression equations determined based on ecoregion for the bankfull discharge versus drainage area, the bankfull cross-sectional area versus drainage area, the bankfull width versus drainage area, the bankfull mean depth versus drainage area and the bankfull discharge versus bankfull cross-sectional area, respectively. The coefficients of determination (R^2) and sample size (n) are also given.

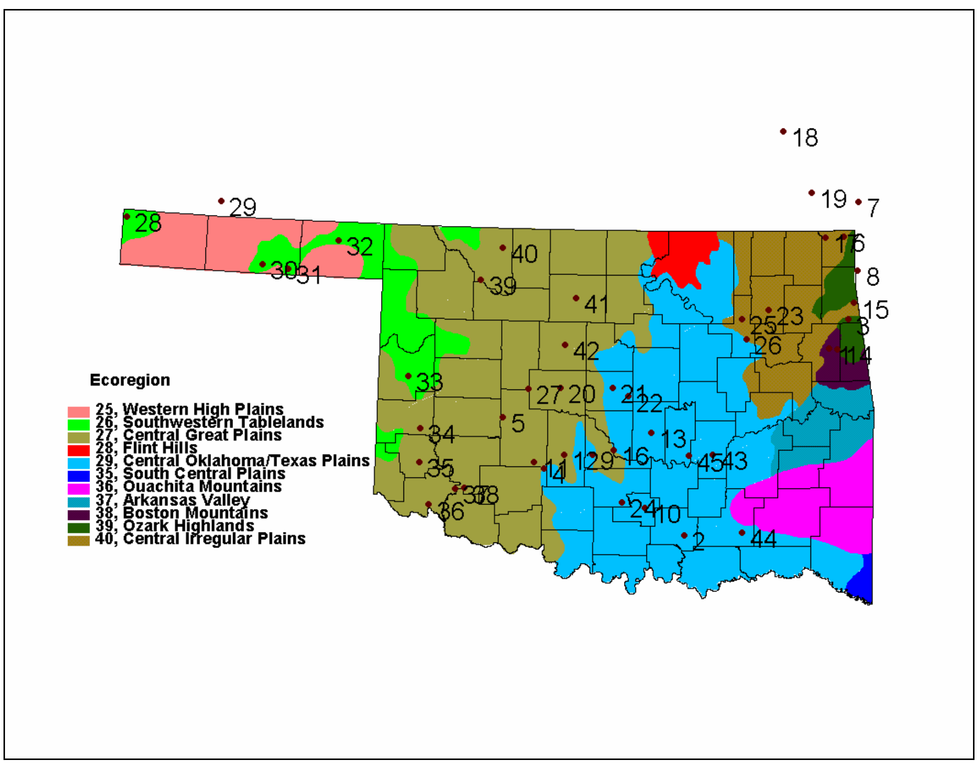

Figure 36: Locations of Oklahoma's ecoregions (Omernik, 1987).

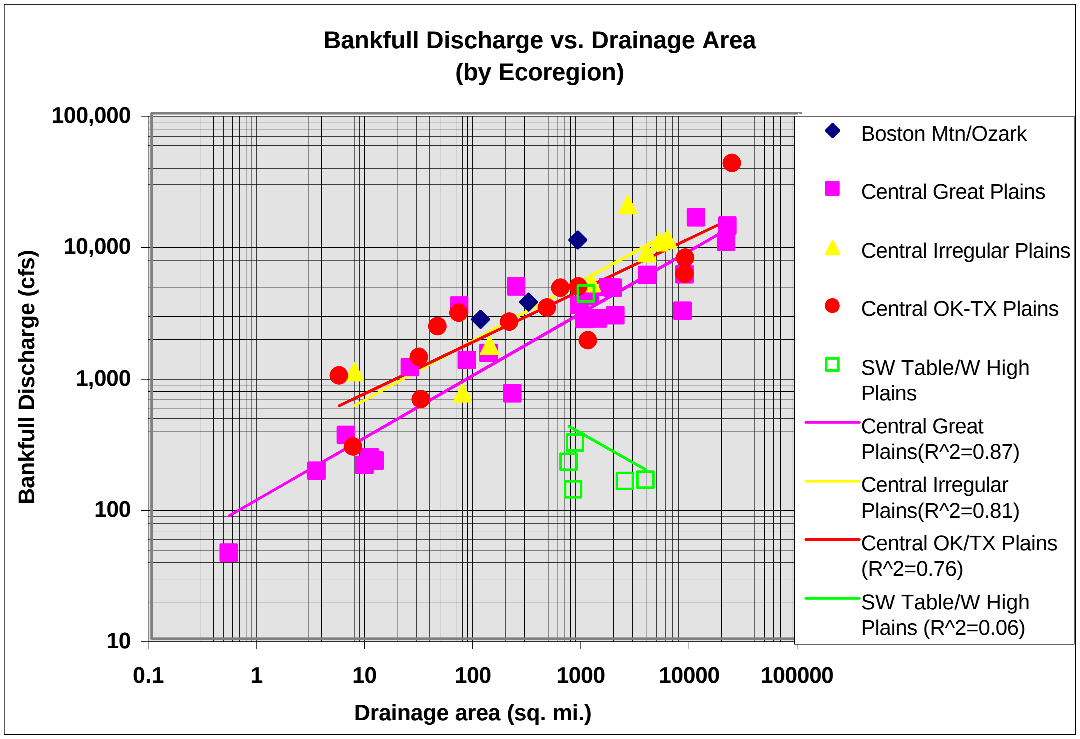

Figure 37: Plot of Bankfull Discharge versus Drainage Area – By Ecoregion.

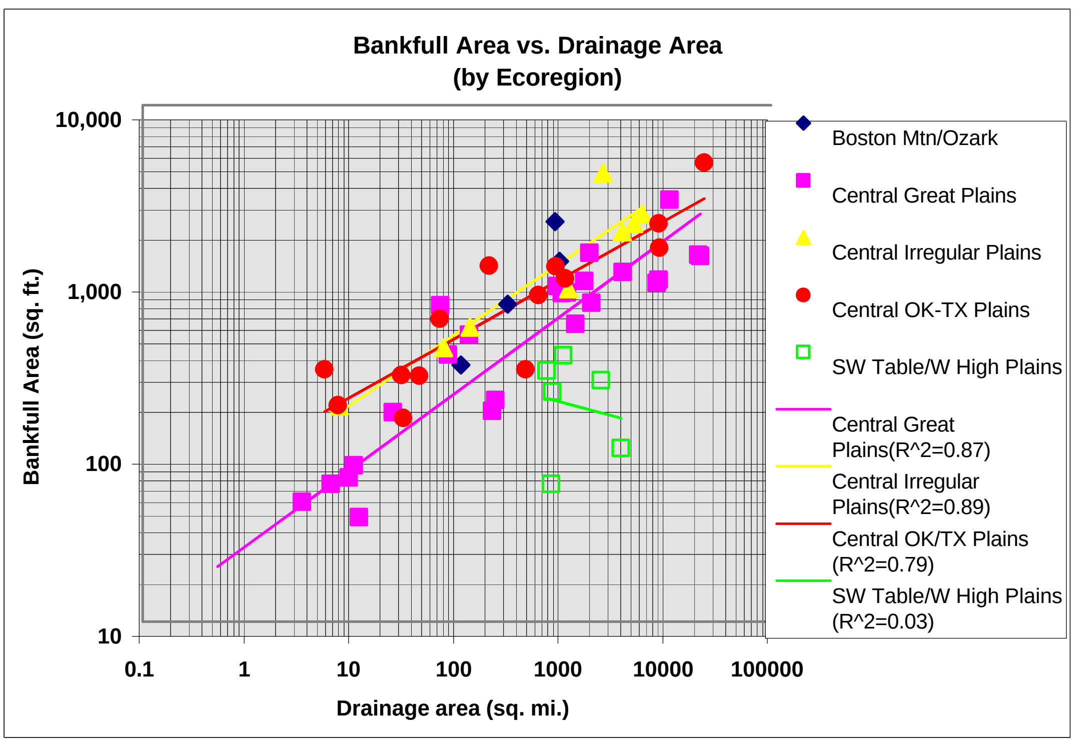

Figure 38: Plot of Bankfull Area versus Drainage Area – By Ecoregion.

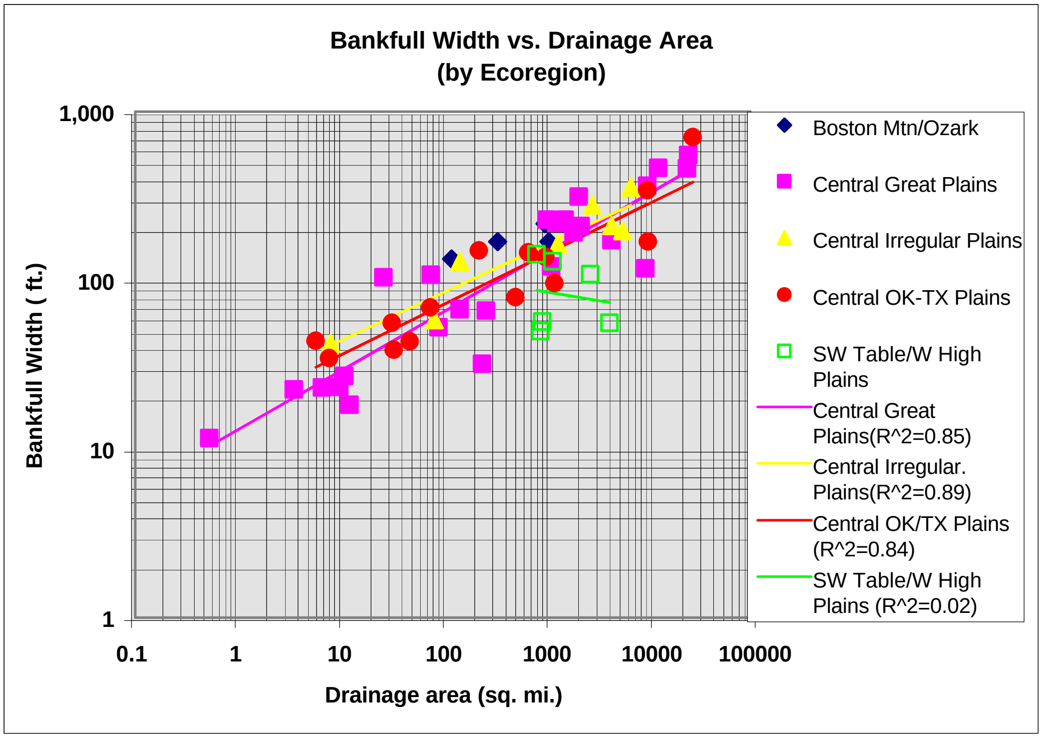

Figure 39: Plot of Bankfull Width versus Drainage Area – By Ecoregion.

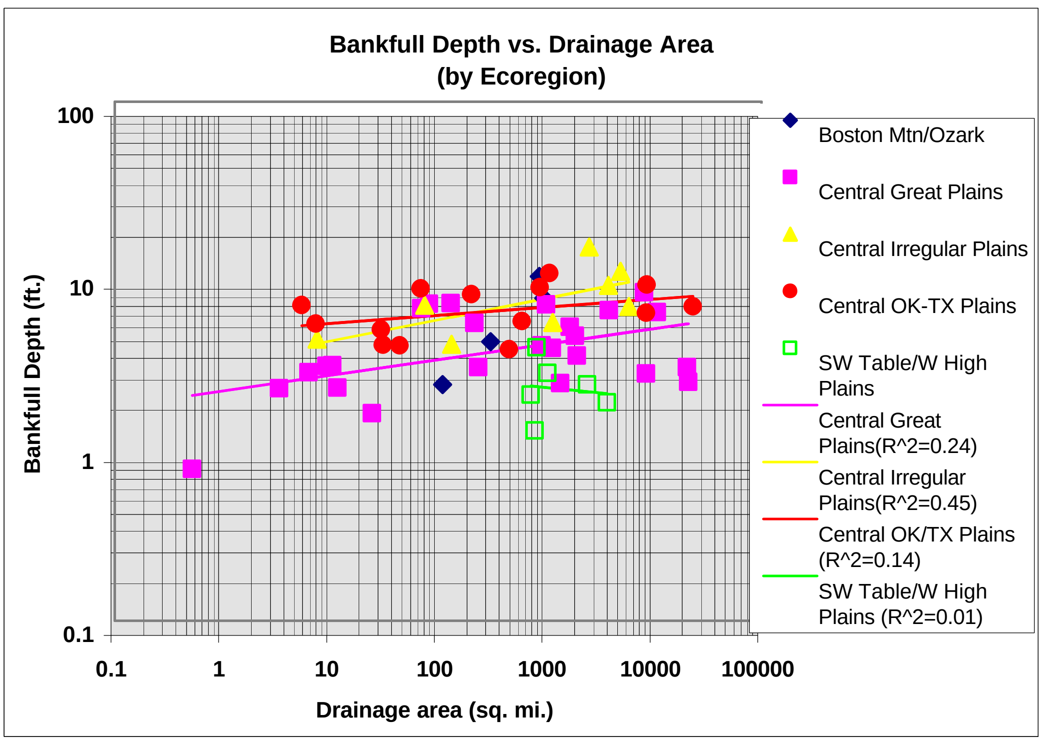

Figure 40: Plot of Bankfull Depth versus Drainage Area – By Ecoregion.

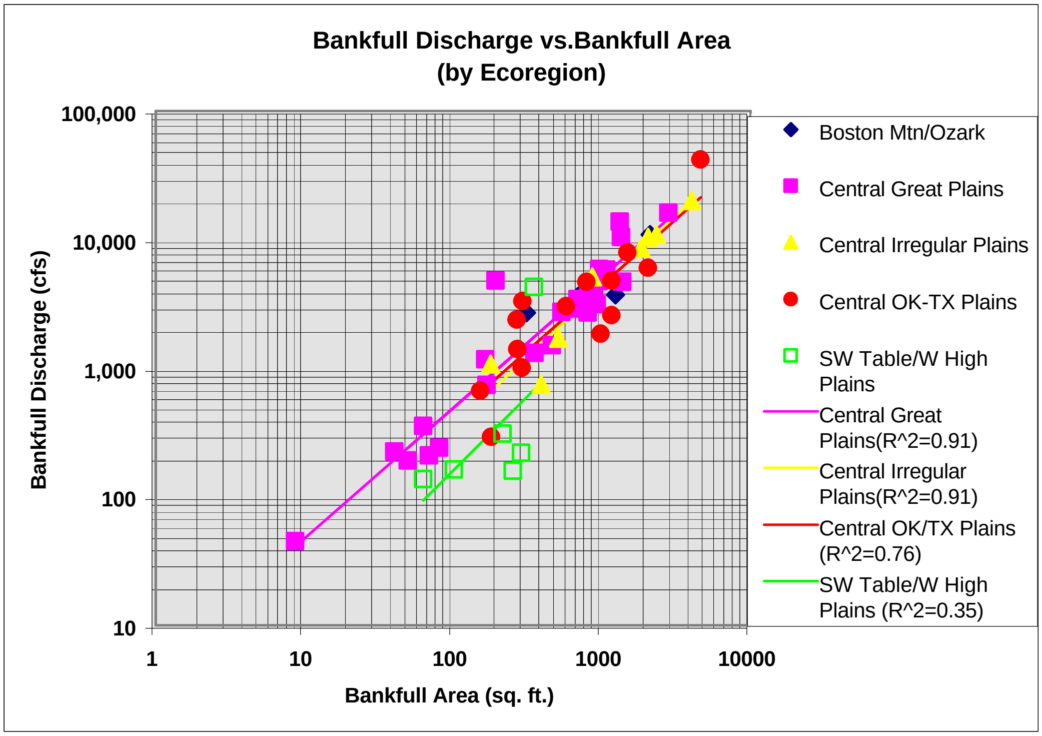

Figure 41: Plot of Bankfull Discharge versus Bankfull Area – By Ecoregion.

Table 24: Regression Equations for Bankfull Discharge versus Drainage Area – By Ecoregion.

Ecoregion	Equation	R^2	n
Central Great Plains	Q=117.41*DA^0.474	0.87	25
Central Irregular Plains	Q=237.83*DA^0.453	0.81	8
Central OK-TX Plains	Q=303.81*DA^0.394	0.76	14
SW Table/W High Plains	Q=8796.31*DA^-0.464	0.06	6
All	Q=186.27*DA^0.398	0.47	57

Table 25: Regression Equations for Bankfull Area versus Drainage Area – By Ecoregion.

Ecoregion	Equation	R^2	n
Central Great Plains	A=27.86*DA^0.444	0.87	25
Central Irregular Plains	A=71.47*DA^0.411	0.89	8
Central OK-TX Plains	A=93.14*DA^0.341	0.79	14
SW Table/W High Plains	A=579.95*DA^-0.163	0.03	6
All	A=46.47*DA^0.387	0.62	57

Table 26: Regression Equations for Bankfull Width versus Drainage Area – By Ecoregion.

Ecoregion	Equation	R^2	n
Central Great Plains	W=13.08*DA^0.354	0.85	25
Central Irregular Plains	W=23.02*DA^0.287	0.89	8
Central OK-TX Plains	W=18.24*DA^0.303	0.84	14
SW Table/W High Plains	W=172.15*DA^-0.103	0.02	6
All	W=16.14*DA^0.317	0.75	57

Table 27: Regression Equations for Bankfull Depth versus Drainage Area – By Ecoregion.

Ecoregion	Equation	R^2	n
Central Great Plains	H=2.13*DA^0.090	0.24	25
Central Irregular Plains	H=3.10*DA^0.124	0.45	8
Central OK-TX Plains	H=4.70*DA^0.047	0.14	14
SW Table/W High Plains	H=3.37*DA^-0.060	0.01	6
All	H=2.81*DA^0.073	0.10	57

Table 28: Regression Equations for Bankfull Discharge versus Bankfull Area – By Ecoregion

Ecoregion	Equation	R^2	n
Central Great Plains	Q=4.54*A^1.016	0.91	25
Central Irregular Plains	Q=2.25*A^1.096	0.91	8
Central OK-TX Plains	Q=3.76*A^1.024	0.76	14
SW Table/W High Plains	Q=0.78*A^1.156	0.35	6
All	Q=2.79*A^1.069	0.82	57

It can be seen in Figures 37 to 41 and Tables 24 to 28 that the ecoregion analysis gives the best overall results. The coefficients of determination for the Central Great Plains and the Central Irregular Plains are very good to excellent, with the exception of the bankfull depth versus drainage area plots. The coefficients of determination for the Central Oklahoma-Texas Plains are good to very good, again with the exception of the bankfull depth versus drainage area plots. Five of the six sites observed within the Southwest Tablelands/WesternHigh Plains are the sites referred to above as Oklahoma-Region 2. The regression equations for this ecoregion therefore give meaningless results. Nevertheless, the rest of the data, with the exception of the bankfull depth versus drainage area, generally result in the best coefficients of determination (R^2) found in the study.

5.4 Mannings' "n" Determination

As stated earlier, the data obtained in this study was also used to estimate Manning's "n" values for each of the sites. The Manning's "n" values determined for each site are presented in Table 29. The estimated values ranged from a minimum of 0.004 to a maximum of 0.135. The mean and median values were 0.038 and 0.030, respectively. Nine values were estimated to be greater than 0.055 and eight values were estimated to be less than 0.01.

Table 29: Manning's "n" values calculated from Geomorphic Survey data.

No	Gauge Station Name	Stream Type	Manning's n
1	Illinois River at Tahlequah	C4c-	0.020
2	Blue River at Milburn	C5c-	0.069
3	Flint Creek near Kansas	B4c	0.007
4	Little Washita River near Cement	G5c	0.020
5	Cobb Creek near Eakley	E5	0.040
6	Spring River at Quapaw	C5c-	0.007
7	Spring River near Waco, MO	F4	0.007
8	Elk River near Tiff City, MO	C4	0.036
9	North Criner Creek near Criner	B5c	0.109
10	Rock Creek near Sulpher	C1	0.020
11	Little Washita River near Cyril	E5	0.039
12	Little Washita River nr E.Ninekah	B5c	0.004
13	Little River near Tecumseh	F5	0.007
14	Baron Fork at Eldon	C4	0.029
15	Spavinaw Creek near Sycamore	C4	0.047
16	Canadian River at Purcell	C5	0.007
17	Neosho River near Commerce	F1	0.061
18	Neosho River at Iola, KS	F4	0.054
19	Neosho River near Parsons, KS	B5c	0.085
20	N. Canadian at El Reno	C5	0.041
21	N. Canadian at Britton Rd	C5	0.035
22	N. Canadian near Harrah	C5	0.025
23	Dog Creek near Claremore	E6	0.052
24	Wildhorse Creek near Hoover	F5	0.025

Table 29: Mannings' "n" values calculated from Geomorphic Survey data (Continued).

No	Gauge Station Name	Stream Type	Mannings' n
25	Coal Creek at Tulsa	B4c	0.009
26	Little Haikey Creek at Tulsa	E5	0.030
27	Canadian River at Bridgeport	C5c-	0.011
28	Cimarron River near Kenton	C5	0.009
29	Cimarron River near Elkhart, KS	C5	0.130
30	Coldwater Creek near Guymon	C5	0.136
31	Palo Duro Creek at Range	C5	0.127
32	Beaver River at Beaver	C5c-	0.034
33	Washita River near Cheyenne	C5	0.028
34	North Fork of Red River near Carter	C5c-	0.025
35	Salt Fork of Red River at Mangum	C5	0.019
36	Salt Fork of Red River near Elmer	C5c-	0.020
37	N. Fork of Red River near Headrick	C5c-	0.017
38	Otter Creek near Snyder	E5	0.022
39	Cimarron River near Waynoka	C5	0.015
40	Salt Fork of Ark. River near Alva	C5	0.060
41	Skeleton Creek near Enid	C1	0.058
42	Cimarron River near Dover	C5c-	0.022
43	Canadian River at Calvin	C5c-	0.014
44	Muddy Boggy Creek near Farris	G5c	0.044
45	Little River near Sasakwa	C5c-	0.041
46	Llano River near Junction,TX	B4c-	0.051
47	San Sabo River at Menard, TX	C4	0.033
48	North Llano River near Junction,TX	F1	0.031

The data presented in Table 29 was sorted by stream type. Minimum, maximum, mean and median values were then calculated for each stream type. These values were then compared to values presented by Rosgen (1996). The results are shown in Table 30.

It may be seen that the calculated values compare reasonably well with the values reported by Rosgen (1996). In addition, Chow (1959) shows pictures of 24 different channels and reports Manning's "n" values for each. Unfortunately, only 4 of the 24 channels are natural channels and, of these, 3 appear to be channel types not represented in the current study. One of the channels shown by Chow (Fig 5-5, No. 15, Pg. 120) however, appears to be a C5 channel for which Chow reports a Manning's "n" of 0.035. The median value calculated for the twelve C5 channels surveyed in this study was 0.031, which agrees well with values reported by Chow. More discussion on Manning's "n" values is included in the following section.

Table 30: Comparison of Calculated Manning's "n" Values with Values Presented by Rosgen (1996) for Various Stream Types.

Stream Type	Study Value					Rosgen's	Mean	Median
	Min	Max	Mean	Median	n	Value	% Difference	% Difference
B	0.004	0.109	0.044	0.030	6			
B4c & B4c-	0.007	0.051	0.022	0.009	3	0.037	-40	-76
B5c	0.004	0.109	0.066	0.085	3	0.044	50	93
C	0.007	0.135	0.039	0.028	29			
C1	0.020	0.058	0.039	0.039	2	0.028	38	38
C4 & C4c-	0.020	0.047	0.033	0.033	5	0.019	74	72
C5	0.007	0.135	0.053	0.031	12	0.034	55	-7
C5c-	0.007	0.069	0.026	0.021	10	0.034	-23	-37
E	0.022	0.052	0.037	0.039	5			
E5	0.022	0.040	0.033	0.035	4	0.032	3	8
F	0.007	0.061	0.031	0.028	6			
F1	0.031	0.061	0.046	0.046	2	0.028	64	64
F4	0.007	0.054	0.030	0.030	2	0.033	-8	-8
F5	0.007	0.025	0.016	0.016	2	0.038	-58	-58
G5c	0.019	0.043	0.031	0.031	2	0.039	-20	-20

6.0 Discussion

The discussion begins with a few comments on the methods used in the geomorphic surveys and analysis of the data. The focus is on the potential sources of error and the implications this could have on interpretation of the data. The discussion continues with an examination of the regional curve data itself. Observed trends and anomalies in the data are discussed and potential explanations are presented. Interpretation of the data is presented as it relates to achieving the objectives of the study, which are to develop regional curves for the entire state of Oklahoma, identify how many hydro-geographic provinces there are in Oklahoma and delineate them, develop regional curves based on stream type, and estimate the Manning's ("n") roughness coefficient based on stream type.

6.1 Geomorphic Surveys and Data Analysis

The methodology used in conducting the geomorphic surveys and analyzing the data was, as are all data collection and analysis efforts, subject to sources of error that could affect the results and therefore the conclusions one would draw from them. The potential sources of error in this study were surveying error, errors in identifying the bank full elevation, errors in transcribing the data, errors in entering the data into the computer, calculation errors in the spreadsheets used to calculate important parameters, errors in the USGS gauge data, and errors in the USGS stage-discharge rating curves.

Errors in surveying, data transcription, data entry, and spreadsheet calculations were controllable to an extent. Surveying errors were minimized by using established leveling survey methods. Rod readings were carefully taken and double-checked if the results were questionable. This was especially necessary for inexperienced personnel, as it is a common mistake to extend the wrong portion of the rod leading to an erroneous reading. Extra care was also taken in establishing turning points when required. Data transcription error was minimized by vigilant note taking. When more than one person was conducting the survey, the person running the rod would announce the reading and the note keeper would parrot the response back. Data entry errors were minimized through slow and deliberate transcribing of the data. The entered data was then double-checked with the written data in the field book. Calculations within the spreadsheet were checked by comparing the results with hand calculations of the same data set. This was done on more than one data set using hand calculations prepared by more than one person.

Errors in identifying the level associated with the bankfull discharge aren't as easy to control. As specified earlier, the bankfull level is the level associated with the discharge that does the most work moving material, and thus is the dominant force that shapes the channel. In many streams, the bankfull level is reasonably easy to identify. There is an obvious break in slope, a change in particle size distribution, and a change in vegetation occurring at roughly the same location along the channel (Rosgen, 1996, Leopold, 1994, U.S.D.A. Forest Service, 1995, U.S.D.A. 1998). If the water level were to rise above this point, the floodplain would be inundated. In these instances, there is no error introduced as a result of bankfull identification.

In other streams, however, identifying the bankfull level is somewhat subjective. There may be several distinct breaks in slope, possibly as a result of an unstable, degrading channel. The vegetation line may be inconsistent, or clearly growing in the channel, possibly as a result of recent drought conditions. Finally, the particle size may be uniform, such as in sand bed channels. Any or all of these factors may lead to incorrect identification of the bankfull level, which would ultimately affect the results of the study.

The most effective control for this source of error is experience and personal knowledge of the stream systems being studied. If the researcher is familiar with the stream, knows the hydrologic history of the stream, and is familiar with the vegetation communities that grow along the stream, then his or her estimation of the bankfull level will most likely be correct. Individuals inexperienced at identifying bankfull features should obtain copies of the U.S. Forest Service field guide for determining the bankfull stage and conducting a stream channel survey (Harrelson, et al., 1994) and the video demonstrating how to identify the bankfull stage (U.S.D.A. Forest Service, 1995). Then they need to spend time in the field looking at creeks and identifying the bankfull level. The author of this paper has been working in the fluvial geomorphology field for five years and has attended several training courses offered by Dave Rosgen, Ann Riley, the International Erosion Control Association and the U.S. Army Corps of Engineers.

With only minimal training and/or experience, an individual should be able to adequately identify the bankfull level in most streams. To demonstrate this fact, consider the Texas data presented in Figures 8 to 12. As previously stated, the data was collected as part of a training exercise the author presented to NRCS personnel in Texas. After spending one day in a workshop in which the concepts of fluvial geomorphology, stream classification and bankfull identification were introduced through lecture, discussion and slides, the class was taken to an active gauge site on the North Llano River near Junction, Texas (site 48). The class was separated into two groups and each group conducted their own geomorphic survey of the site without being told where the bankfull level was. One group reported the results from one cross-section; the other group reported the results from two distinct cross-sections. None of the cross-sections reported were located within the same reach. The following day each of the groups went to a different stream, one to the Llano River near Junction, Texas (site 46) and the other to the San Sabo River at Menard, Texas (site 47). The group that went to the San Sabo River reported results for two cross-sections. The observed variation between the groups appears to be within acceptable limits, as can be seen in Tables 2 and 3 and Figures 8 to 12. Nevertheless, the data serves to show the extent of variability in identifying bankfull features that would be encountered by different groups of people. The individuals that performed these surveys had little or no knowledge of fluvial geomorphology yet their results were all similar.

It was stated previously that the bankfull discharge is often related to a recurrence interval of from 1.0 – 1.8 years, as determined using a flood frequency analysis (Rosgen, 1996, Leopold, 1994, U.S.D.A. Forest Service, 1995, U.S.D.A. 1998). This fact provides one with a second check on the estimated bankfull level. If the discharge associated with the estimated bankfull level has a return interval of less than a year, or more than 1.8 years, the estimated bankfull level is probably incorrect and the site should be re-visited.

An apparent exception to this rule was encountered in this study, however. Referring to Table 3, it can be seen that the return interval for site 22, the North Canadian River near Harrah, with an estimated bankfull discharge of 8,602 cfs, was reported to be 3.65 years. Normally, this would indicate that the assumed bankfull level was too high. However, return intervals for sites 20 and 21, the North Canadian River at El Reno and the North Canadian River at Britton Road, which are approximately 68 miles and 18 miles upstream of the Harrah site respectively, were reported to be 1.75 and 1.45, respectively. Estimated bankfull discharges at the North Canadian River at El Reno and the North Canadian River at Britton Road sites were reportedly 8,143 cfs and 8,514 cfs, respectively. In addition, the reported discharge and hydraulic geometry data for site 22 compare favorably with the rest of the data. Therefore, it appears, that there is a discrepancy in the data obtained from USGS for these sites. A possible source of the discrepancy could be due to an inaccurate stage-discharge rating curve for the site, although the actual cause of the discrepancy is unknown.

Although critical to the study, the researchers had no control over errors in the USGS gauge and stage-discharge rating curve data since it was collected, compiled and analyzed by USGS personnel. Gauge data, as mentioned earlier, was obtained from USGS telemetry data available on the Internet. Both the stage and discharge were available for most sites, although the stage is the parameter that USGS actually measures and was the parameter of most interest in this study. The bankfull stage, the stage associated with the bankfull discharge, was determined, as previously discussed, by adding the difference between the elevation of the bankfull indicators and the elevation of the water surface at the time of the survey to the stage reading at the time of the survey. The bankfull discharge was then determined from the stage-discharge curve using the bankfull stage thus determined. Therefore, errors in determining the bankfull discharge may arise from errors in the stage data for the gauge or from errors in the stage-discharge rating curve.

Errors in the reported stage may arise from several factors, including inoperable equipment due to mechanical or electric failure, or from blockage of the bubbler intake by debris or sand, or as a result of changes in the channel such as degradation, aggradation or channel migration. Errors in the stage-discharge rating curve may arise as a result of incorrect stage readings, incorrect flow measurements taken at a given stage, or changes in the channel. Errors in either would affect the results obtained from the data.

There are steps that could have been taken in the field to minimize the potential error from these sources, but time constraints and accessibility prohibited them from being employed. Stage data, as reported on the Internet, could have been checked by obtaining a key to the USGS gauge stations and using the wire weight to measure the stage. The stage discharge curve could have been checked, at least at base flow, by measuring the discharge at the time the survey was conducted. Unfortunately, this was not done, but it is highly recommended that in future studies, the researchers obtain a key from USGS and read the stage directly from the wire weight.

6.2 Regional Curves

The discussion will now turn to the results of the data, as it relates to achieving the objectives of the study. Referring to Figures 8 – 10 it can be seen that there is an obvious trend for the bankfull discharge, the bankfull cross-sectional area, and the bankfull width to increase with increasing drainage area, which one would expect because of the larger flows coming off of a larger drainage area. In Figure 11, which shows the bankfull depth versus drainage area data, it can be seen that there is only a slight increase in channel depth and considerably more scatter. This too is to be expected as it has been found that the depth of a channel is only slightly dependent on drainage area. There is also a trend for the bankfull discharge to increase with increasing bankfull area, or vice versa as can be seen in Figure 12. This is also expected as one would expect larger flows to require larger channels for effective transport.

As stated earlier, there are four sets of data plotted on these graphs, Oklahoma-Region 1, Oklahoma-Region 2, Texas and NRCS. The NRCS data collected in the Sugar Creek watershed fits well with the data presented in this study, as does the data collected from sites in central Texas. Data from five of the sites surveyed in Oklahoma for this study however, exhibit a bankfull discharge that is an order of magnitude lower than the remaining data for the same drainage area. These five data points, which have site numbers ranging from 29 to 33, are all located in the panhandle or far western Oklahoma, as can be seen in Figure 7. The data for Oklahoma was therefore split into two “Regions,” as previously mentioned. Doing so allowed for development of a regression equation for the data with a much higher coefficient of determination (0.80 as compared to 0.47), but is such an action justifiable or is it just an attempt to make the data fit?

Referring to Table 29, it can be seen that the Manning’s “n” values estimated from the hydraulic data obtained in the field and from the USGS for sites 29 to 31 are 0.130, 0.135 and 0.127, respectively. These values are an order of magnitude higher than the values reported from most of the other stations. Since discharge is inversely proportional to Manning’s “n”, this phenomenon would be expected if the reported discharge in the channel was under-reported by a factor of ten. Therefore, gauge error may explain why data from these three sites was significantly different from the rest of the sites. However, Manning’s “n” values determined for the other two sites, sites 32 and 33, were not significantly different than those reported at other sites in the study, so this explanation seems doubtful.

Another possible explanation for the observed differences in the data for these sites is the geographic location of the sites in relation to the High Plains Aquifer. Figure 42 shows the location of the High Plains Aquifer in relation to the geomorphic survey sites. It can be seen that four of the five sites, sites 29 to 32 are geographically located over the aquifer.

The fifth site, site 33, is not located over the aquifer, but the majority of its watershed and all of its receiving streams are. This is significant, as several reports have been released by USGS on drawdown of the aquifer and the effects that it has had on surface water hydrology in the region (Dugan and Schild, 1992; Wahl and Tortorelli, 1997; Luckey and Becker, 1999).

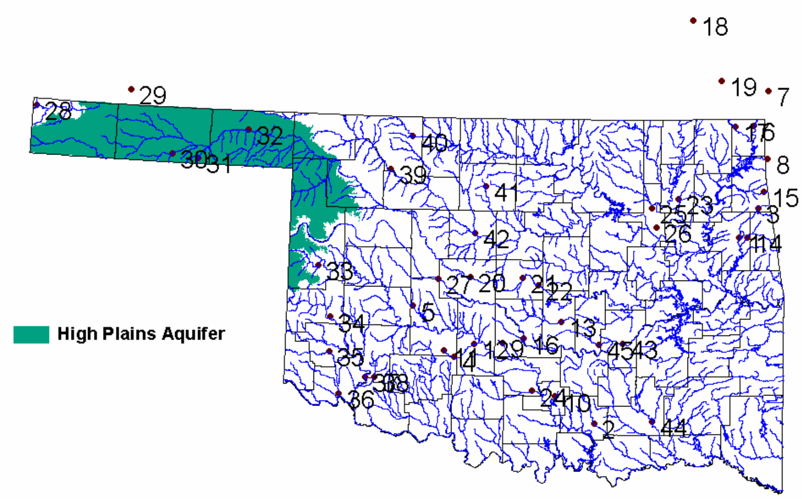

Figure 42: Location of the High Plains Aquifer in Oklahoma.

In particular, a study by Wahl and Tortorelli (1997), in which they report on “Changes in flow in the Beaver-North Canadian River basin upstream from Canton Lake, Western Oklahoma” seems to support this explanation. Three of the five data points of concern here (sites 30-32) are included in the study by Wahl and Tortorelli. Among other things, Wahl and Tortorelli report that the average annual discharge in the Beaver River at Beaver (site 32) decreased by 82 percent between the early period (which they report as ending in 1971) and the recent period (which they report as 1978-1994). The medians of the annual peak discharges reportedly decreased by 86 percent over the same time period. Wahl and Tortorelli state that, “A primary mechanism producing these decreased stream flows appears to be the depletion of ground water in the High Plains aquifer that underlies more than 90 percent of the basin.”

The results of Wahl’s and Tortorelli’s work seems to support the hypothesis that the geographic location of the sites in relation to the High Plains Aquifer is responsible for the decreased bankfull discharge values from the five sites of concern, as compared to the rest of the data. In addition, the fact that two of the sites of concern here (sites 29 and 33) are outside of the range of data evaluated by Wahl and Tortorelli and yet are geographically connected to the High Plains aquifer and exhibit the same relative reduction in bankfull discharge seems to compliment their work and add further weight to their postulation. However, to be conclusive, further work in this area is warranted.

The plots shown in Figures 8 to 12 and the regression equations presented in Equations 6, 8, 10 and 14, exhibit good to very good correlations, and therefore may be used as a starting point to estimate the bankfull discharge, the bankfull area and the bankfull width, respectively, to use in natural channel design in Oklahoma. However, thirteen different stream types were represented by the data so the data was sorted by stream type to determine if the bankfull discharge and channel dimensions are dependent on stream type.

Referring to Figure 13 and the regression equations provided in Table 4, one can see some difference in the resulting equations for the bankfull discharge versus drainage area, and, with the exception of type B and type C channels, the coefficients of determination (R^2) are fairly low. The same thing may be said for the bankfull area versus drainage area as may be seen in Figure 14 and the regression equations provided in Table 5. Thus the bankfull discharge and the bankfull area were not observed to be dependent on stream type.

Referring to Figure 15 and the regression equations provided in Table 6, it may be seen that the widths are somewhat dependent on stream type. For a given drainage area, type C channels are typically wider than other types, type B channels are generally wider than type G channels, and type E channels are typically the narrowest, although there is some overlapping of the data. The coefficients of determination (R^2), however, though good for type B channels, are only fair to poor for other types. The relationships of bankfull depth versus drainage area show no dependence on stream type as may be seen in Figure 16 and the regression equations provided in Table 7. Overall it therefore appears that little is to be gained by sorting the existing data by stream type.

Obviously, there is a vast difference in geology, rainfall patterns, climate and vegetation communities across the state, so it was felt that the state should probably be divided into more than one hydro-geographic province. In fact, because the literature stresses the importance of developing these relationships for hydro-geographic provinces, one of the objectives of this study was to identify how many hydro-geographic provinces there are in Oklahoma and delineate them. This was accomplished, as stated earlier by sorting the data based on river basin, climate zone, mean annual precipitation, and ecoregion.

Figures 19 to 23 and the regression equations given in Tables 9 to 13 give the results of sorting the data by river basin. The relationship of bankfull discharge versus drainage area appears to be somewhat dependent on river basin, although the results are mixed as may be seen in Figure 19 and the regression equations given in Table 9. The coefficients of determination (R^2) for the Grand Neosho, Arkansas and Canadian river basins in particular are good, for the North Canadian river basin they are fair, and for the Cimarron, Red and Washita river basins they are poor. Results are similarly mixed for the bankfull area versus drainage area and the bankfull width versus drainage area data, as shown in Figures 20 and 21, respectively, and the regression equations provided in Tables 10 and 11, respectively. The relationship of bankfull discharge versus bankfull area also appears to be somewhat dependent on river basin, as may be seen in Figure 23 and the regression equations provided in Table 13. Once again, the coefficients of determination (R^2) for this relationship are better for the most part than for the other relationships. Thus, although sorting the data by river basin seemed to indicate some relation of the data to river basin, the coefficients of determination (R^2) for some of the basins are not that good, indicating that delineating hydro-geographic provinces based on river basin is probably not sufficient.

Figures 25 to 29 and the regression equations given in Tables 14 to 18 give the results of sorting the data by climate zone. It may be seen that for a given sized drainage area, channels in the northeast climate zone transport a larger bankfull discharge, have a larger bankfull cross-sectional area and a larger bankfull width than do channels in the southwest and central climate zones. Similarly, channels in the central climate zone transport larger bankfull discharges and have larger channels than do channels in the southwest climate zone draining similarly sized watersheds.

The coefficients of determination (R^2) for bankfull discharge versus drainage area, however, once again exhibit mixed results, as may be seen in Figure 25 and the regression equations given in Table 14. The data for the Southwest climate zone was found to have a very good R^2 value, data for the Central and Northeast climate zones had good R^2 values and data for the Panhandle had a poor R^2 value. The remaining climate zones had insufficient data, so no conclusions may be drawn from these regions.

The data for bankfull area versus drainage area presented in Figure 26 and the regression equations given in Table 15 also show mixed results, although the coefficients of determination (R^2) are generally higher than previously observed. The coefficients of determination (R^2) for the Northeast and Southwest climate zones are very good, whereas they are good for the Central climate zone and poor for the Panhandle. Again, the remaining climate zones had insufficient data, so no conclusions may be drawn from these regions. The data for bankfull width versus drainage area presented in Figure 27 and the regression equations given in Table 16 exhibit similar results. R^2 values are very good for the

Northeast and Southwest climate zones, good for the Central climate zone, and poor for the Panhandle. Data for bankfull depth versus drainage area presented in Figure 28 and the regression equations given in Table 17 again show poor correlation for these parameters.

The data for bankfull discharge versus bankfull area presented in Figure 28 and the regression equations given in Table 18 also give mixed results. The coefficients of determination (R^2) for the Northeast and Southwest climate zones are very good, whereas they are poor for the Central and Panhandle climate zones. The mixed results obtained from the data sorted by climate zone indicate that climate zone is not a sufficient basis for delineating hydro-geographic provinces.

Figures 31 to 35 and the regression equations given in Tables 19 to 23 give the results of sorting the data by mean annual precipitation. Plots for two precipitation zones, 23 – 33 inches and 34 – 43 inches, result in good to very good correlation of the data to the regression equations, i.e. coefficients of determination (R^2) between 0.7 and 0.9. Plots for the remaining precipitation zone for which there was sufficient data to evaluate (10 – 22 inches) show poor correlation. It may be seen in Figures 31 to 33 that there is a tendency for the bankfull discharge, the bankfull area, and the bankfull width for a given drainage area to increase with increasing rainfall as one would expect. Also, it may be seen in Figure 30 that the dividing line between the 23 – 33 inch precipitation zone and the 34 – 43 inch precipitation zone bisects the state roughly in the location of Interstate 35. Thus one would expect channels east of Interstate 35 to have a larger bankfull discharge, a greater bankfull area and a greater bankfull width for a given drainage area than channels west of Interstate 35, which is what was observed. Therefore, a designer attempting to design a natural channel in Oklahoma would expect to design a larger channel for the same drainage area in eastern Oklahoma than in western Oklahoma. The regression equations provided in Tables 19 to 23 are therefore sufficient to delineate rough hydro-geographic provinces for the state, but this may be improved upon with more data from the other rainfall regions.

Figures 37 to 41 and the regression equations given in Tables 24 to 28 give the results of sorting the data by ecoregion. Regressions for three of the five ecoregions represented by the data, the Central Great Plains, the Central Irregular Plains and the Central Oklahoma-Texas Plains result in high coefficients of determination (R^2) for plots of bankfull discharge, bankfull area and bankfull width versus drainage area. Regressions for the Boston/Ozark Mountain ecoregions were not conducted due to the limited number of sites surveyed in the ecoregion. Regressions for the Southwest Tablelands/Western High Plains are affected by the presence of the High Plains Aquifer, as discussed earlier. Nevertheless, the results given in Figures 37 to 41 and the regression equations given in Tables 24 to 28 may be used to appropriately size a natural channel based on the ecoregion that the stream is located in.

A lot of data and a number of regression equations have been presented in this study. Based on the data along with the resulting regression equations and the previously discussed coefficients of determination (R^2), it appears that the best criteria to use to delineate the state into hydro-geographic provinces is ecoregion or mean annual precipitation.

A question that must be considered is this: “What is the implication of using some of the other regression equations? How would the design discharge and the channel dimensions change based on the various equations?” To illustrate this, consider two separate natural stream channels that are to be constructed. Each has a drainage area of 100 square miles. One channel is located in southwestern Oklahoma, lies within the Washita River basin, the Southwest climate zone, the Central Great Plains ecoregion and receives between 23 to 33 inches of precipitation a year. The other channel is located in northeastern Oklahoma, lies in the Grand Neosho River basin, the Northeast climate zone, the Central Irregular Plains ecoregion and receives between 34 to 43 inches of precipitation a year.

Table 31 shows the bankfull discharge, the bankfull area, the bankfull width and the bankfull mean depth as calculated for these sites using the regression equations developed for the entire state, by river basin, by climate zone, by mean annual precipitation and by ecoregion. The first row gives the bankfull discharge the bankfull area, the bankfull width and the bankfull mean depth calculated for a 100 square mile watershed based on the regression equations provided in Equations 6, 8, 10 and 12, respectively. Obviously, the results for the two sites are the same since the same equations were used to calculate the various parameters.

Table 31: Comparative results of bankfull discharge and bankfull channel dimensions for 100 square mile watersheds in southwest and northeast Oklahoma using various regression equations.

	Southwest Oklahoma site				Northeast Oklahoma site			
Curve	Q, cfs	A, sq. ft.	W, ft	H, ft	Q, cfs	A, sq. ft.	W, ft	H, ft
Entire State	1439.44	308.49	72.95	4.16	1439.44	308.49	72.95	4.16
River Basin	971.33	191.23	52.12	3.48	2059.60	502.60	88.78	5.64
Climate Zone	869.06	190.21	48.60	3.90	2356.86	531.04	95.04	5.61
Rainfall	983.04	204.64	63.13	3.22	2038.34	506.06	77.37	6.30
Ecoregion	1041.61	215.27	66.77	3.22	1915.43	474.38	86.32	5.49

The second row in Table 31 gives the bankfull discharge and bankfull channel dimensions based on river basin using the regression equations provided in Tables 9 to 12. The differences in bankfull discharge and bankfull channel dimensions calculated for the two sites are significantly different; they reflect the variation in the data used to develop the regional curves for these river basins. However, as discussed earlier, the coefficients of determination (R^2), though relatively high for the Grand Neosho River basin were low for the

Washita River basin, indicating a significant amount of scatter in the data used to develop the regression equations for this basin.

The third, fourth and fifth rows in Table 30 give the bankfull discharge and bankfull channel dimensions based on Climate Zone, Mean Annual Precipitation and Ecoregion, using the regression equations provided in Tables 14 to 17, Tables 19 to 22 and Tables 24 to 27, respectively. As discussed earlier, the coefficients of determination (R^2) for the Northeast and Southwest Climate zones were fairly high, as were the coefficients of determination (R^2) for the 23 to 33 inch and 34 to 43 inch mean annual precipitation zones and the Central Great Plains and Central Irregular Plains ecoregions. The calculated bankfull discharges and channel dimensions using regression equations based on climate zone, mean annual precipitation and ecoregion are thus similar. In particular, the calculated bankfull discharges and channel dimensions using regression equations based on mean annual precipitation and ecoregion are within 10 to 15% of each other. This is within the acceptable limits of standard flow measuring techniques, as discussed with various USGS field personnel and others who routinely conduct stream flow measurements, and reinforces the earlier analysis and supports the conclusion that the state should be delineated into hydro-geomorphic regions based on either mean annual precipitation or ecoregion.

It can also be observed in Table 31 that the values calculated for the site in southwest Oklahoma using the regression equations based on climate zone, mean annual precipitation and ecoregion are lower than the values calculated using the regression equations for the entire state. Similarly, the values calculated for the site in northeast Oklahoma are higher using the regression equations based on climate zone, mean annual precipitation and ecoregion than the values calculated using the regression equations for the entire state. Thus, the regression equations developed for the entire state have the effect of "smoothing" the regional trends, which also supports the conclusion that the state should be delineated into hydro-geomorphic regions based on either mean annual precipitation or ecoregion.

6.3 Manning's "n" Determination

The results of the Manning's "n" determination were presented previously in Table 29. The majority of the values were determined to be within the range of published values (0.01 to 0.055), however nine values were estimated to be greater than 0.055 and eight values were estimated to be less than 0.01. The explanation for these high and low values is not clear, although it may indicate errors in the USGS gauge and stage-discharge rating curve data. As previously discussed, there are steps that could have been taken in the field to minimize the potential of gauge error, but time constraints and accessibility prohibited them from being employed. It is highly recommended that in future studies, precautionary steps be included to check the accuracy of the USGS gauge measurement data.

As part of this study, plots were developed showing the relationship between bankfull area and bankfull discharge, as may be seen in Figures 12, 17, 23, 29, 35 and 41. Regression equations for these relationships were provided in Equation 14 and Tables 8, 13, 18, 23 and 28. The significance of these relationships was evaluated by calculating the bankfull discharge for each site, from the bankfull cross-sectional area, using the regression equations given in Table 28, and comparing the results to the bankfull discharge calculated from Manning's equation using the "n" values recommended by Rosgen for various stream types (Rosgen, 1996). In both cases, the bankfull discharge was calculated using parameters measured in the field, i.e., the bankfull area for the regression equations, and, the bankfull area, the longitudinal slope and the hydraulic radius for Manning's' equation. Both values were plotted against the bankfull discharge as determined from the observed bankfull stage at each site and data obtained from the USGS, as previously described. The resulting plot is shown in Figure 43.

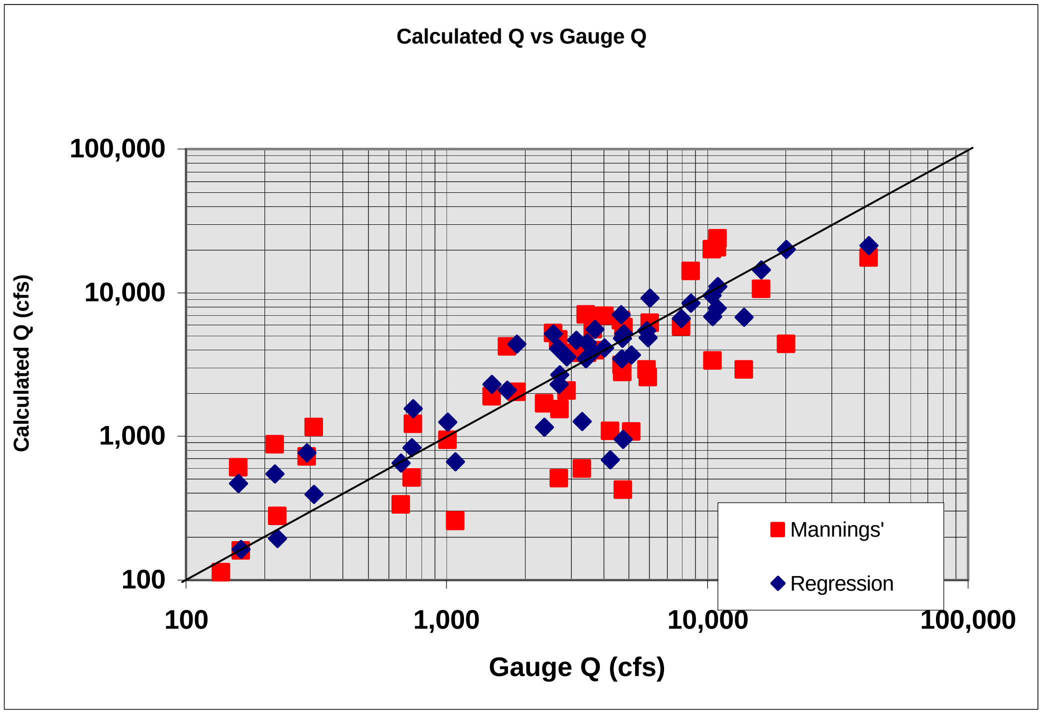

Figure 43: Plot of Calculated Bankfull Discharge versus Measured Bankfull Discharge.

It was found that the bankfull discharge calculated using the regression equations provided in Table 28 more closely matched the bankfull discharge as determined from USGS gauge data than did bankfull discharge values calculated using the Manning's equation and Manning's "n" values reported by Rosgen. This may be seen in Figure 43 in that the dark line represents the line of equality between calculated and observed bankfull discharge and the data calculated from the regression equation typically lies closer to this line than does the data calculated from the Mannings' equation, although in both cases there is quite a bit of scatter.

Thus, it appears from the data, that one can estimate the bankfull discharge of a stream if they can accurately estimate the bankfull area. This would save some time, as one doesn't need to know the drainage area or the longitudinal slope of the channel to estimate the bankfull discharge. However, this relationship should be used cautiously, and only in fairly low gradient (< 1%) streams with silt, sand or small gravel substrates. Also, it should only be used as a quick estimate. In general, it is recommended that for design purposes the regression equations provided in Tables 19 to 22 and Tables 24 to 27 for various regions of mean annual precipitation and ecoregion, respectively, be used.

7.0 Conclusions and Recommendations

The primary objective of this study was to develop regional discharge curves for the state of Oklahoma. Secondary objectives were threefold: identify how many hydro-geographic provinces there are in Oklahoma and delineate them, with potential delineations based on average annual rainfall, ecoregion (Omernik, 1987), major river basin (State of Oklahoma, 1992) and climate (USGS, 1999); develop regional curves based on stream type; and estimate the Manning's ("n") roughness coefficient at bankfull for each site surveyed to determine if there is any relationship between stream type and Manning's "n".

Geomorphic surveys were conducted at 48 sites located in Oklahoma, Kansas, Texas and Missouri. Thirteen different stream types were identified. There were three B4c's, three B5c's, two C1's, four C4's, one C4c-, nine C5's, thirteen C5c-'s, four E5's, one E6, two F1's, two F4's, two F5's and two G5c's. Drainage areas ranged from 5.45 mi^2 to 23,151 mi^2, with mean and median values of 3,275 mi^2 and 984 mi^2, respectively. The bankfull discharges ranged from 136.7 cfs to 41,750 cfs, with mean and median values of 5,275 cfs and 3,444 cfs, respectively. The return interval associated with the bankfull discharge ranged from 1.01 years to 3.65 years, with mean and median values of 1.41 years and 1.33 years, respectively.

Regional curves, which provide relationships between bankfull discharge and drainage area and between bankfull channel dimensions and drainage area, were first developed using the entire data set. It was found that five sites, all located in the panhandle or far western Oklahoma, had bankfull discharges that were an order of magnitude lower than the remaining data for the same drainage area. Four of the five sites were found to be geographically located over the High Plains aquifer. The fifth site, though itself not located over the aquifer, has the majority of its watershed and all of its receiving streams located over it. This was felt to be significant, as several reports have been released by the USGS on drawdown of the aquifer and the effects that it has had on surface water hydrology in the region (Dugan and Schild, 1992; Wahl and Tortorelli, 1997; Luckey and Becker, 1999). Wahl and Tortorelli, in fact, report that the average annual discharge in the Beaver River at Beaver decreased by 82 percent between the early period (which they report as ending in 1971) and the recent period (which they report as 1978-1994) and that the medians of the annual peak discharges decreased by 86 percent over the same time period. Excluding the data from these five sites from the regression analysis resulted in regional curves for the state with fairly high coefficients of determination (R^2).

Since thirteen different stream types were represented by the data and one of the objectives of the study was to develop regional curves based on stream type, the data was sorted by stream type to determine if this factor was significant in determining the bankfull discharge and channel dimensions. The bankfull discharge, the bankfull area and the bankfull mean depths were not observed to be dependent on stream type. The bankfull widths were found to be somewhat dependent on stream type, although the coefficients of determination (R^2) were low. Therefore, little was gained by sorting the data by stream type.

The data was next sorted based on river basin, climate zone, mean annual precipitation, and ecoregion. It was found that regression equations for the plots sorted by mean annual precipitation and ecoregion resulted in the best coefficients of determination (R^2). It was also found that the two methods gave similar results for the bankfull discharge and the bankfull channel dimensions. Therefore, it is recommended that the state be delineated into at least two hydro-geomorphic regions based on mean annual precipitation or ecoregion. The plots presented in Figures 31 to 35 and the regression equations given in Tables 19 to 23 should be used to determine the bankfull discharge and bankfull channel dimensions based on mean annual precipitation, or the plots presented in Figures 37 to 41 and the regression equations given in Tables 24 to 28 should be used to determine the bankfull discharge and bankfull channel dimensions based on ecoregion.

The results of the Manning's "n" determination indicated that the majority of the Manning's "n" values were within the range of published values (0.01 to 0.055), however nine values were estimated to be greater than 0.055 and eight values were estimated to be less than 0.01. Mean and median values were 0.038 and 0.029, respectively. Observed values somewhat agreed with the “n” values recommended by Rosgen for various stream types (Rosgen, 1996), although there was considerable scatter in the data. A comparison of bankfull discharges estimated using regression equations developed for bankfull discharge versus bankfull cross-sectional area (Table 28) and bankfull discharges calculated using Manning’s’ equation was performed. It was found that the bankfull discharge calculated using the regression equations more closely matched the bankfull discharge, as determined from USGS gauge data, than did bankfull discharge values calculated using the Manning’s equation and Manning’s “n” values reported by Rosgen.

All in all, it is felt that the objectives of the study were accomplished. The results presented herein fill a gap in the literature and may be used with some confidence to calculate bankfull discharges and bankfull channel dimensions for streams in Oklahoma. Much was learned in the study, including some unexpected findings. However, much work remains to be done in this field of study. Many gauge sites have yet to be surveyed, especially in the southeast portion of the state, and very little information is available on small streams draining watersheds of less than 2 square miles. In addition, more work certainly needs to be conducted to evaluate the impacts to surface waters in the vicinity of the High Plains aquifer.

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