Masters Plan B Report

Watershed Response Factor and Rainfall-Based Regional Curves

A New Tool Used to Predict Hydraulic Geometry Relationships

Submitted By

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ABSTRACT

Over the last century, engineers and fluvial geomorphologists have been working to understand the complex interactions between rivers and their watersheds in hopes of restoring a state of quasi-equilibrium following an era of anthropogenic-driven degradation. To aid in these restoration efforts, regional curves have been developed across the nation to help predict stable channel dimensions. This study combines 48 published regional curve studies into a large, national dataset to produce a combined, geolocated dataset in GIS shapefile format to be used by hydraulic engineers to quickly locate and reference summary data for existing regional curve studies. Additionally, it is hypothesized that average annual rainfall plays an important role in determining the geometric characteristics of a stream. The primary goal of this project is to introduce two new tools used to predict channel dimensions in areas lacking existing regional curves. These tools are referred to as the Watershed Response Factor (WRF) and Rainfall-Based Regional Curves. Both methods use average annual rainfall values and drainage area to predict bankfull cross-sectional area. These tools are intended to fill geographic gaps between existing studies for areas where regional curves have not been developed. Resulting values of bankfull cross-sectional area estimated by these two methods are expected to be of similar accuracy to published regional curves. Therefore, it is proposed that future regional curve studies be discontinued.

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INTRODUCTION

Streams and rivers are powerful natural forces responsible for shaping much of the world as we know it. Almost too complex and variable to comprehend, the interactions between river and surrounding landscape provide an ecosystem to both aquatic and terrestrial life. These organisms are adapted to, and dependent on, the organized chaos of the interrelationships between hydrologic, climatic, geologic, and biologic characteristics of the drainage basin. Although each of these basin characteristics can be extremely variably over space and time, a state of quasi-equilibrium can often be observed between all forces at work. However, this delicate state can be disrupted by natural or anthropogenic changes to the river or its watershed. Once change is initiated, the river tends to shift its controlling variables in a direction as to absorb the effect of change in search of a new equilibrium (Mackin 1948). Natural change often occurs over a long enough period such that rivers can adjust simultaneously to maintain a state of quasi-equilibrium. More recently, however, human-induced alterations of the landscape, as well as direct modifications to the river corridor and natural flow regime, are shifting rivers out of equilibrium on a global scale at an alarming rate.

Over the last century, engineers and scientists have been working to understand the complex interactions between rivers and their watersheds in hopes of restoring a state of quasi-equilibrium following an era of anthropogenic-driven degradation. Presently, qualitative relationships and mathematical formulas have been insufficient in capturing the full complexity of rivers. Although the exact interrelations of river characteristics are still unknown, much knowledge has been gained over the last century by collecting data, making observations, and developing relationships between measurable characteristics. Largely since the 1950s, empirical relationships have been developed to explain recognizable patterns and trends in data. Leopold and Maddock (1953) developed the foundational theory of "hydraulic geometry" which uses theoretical and empirical methods to better understand the link between independent and dependent variables. Many others have expanded upon their work to produce valuable tools for stream restoration engineers. Dunne and Leopold (1978) observed a hydraulic geometric relationship between channel dimensions and drainage area. They grouped these relationships by physiographic region to produce plots known as "regional curves". Regional curves have been developed throughout the country to help predict the size and shape of rivers in varying regions to aid in river restoration design.

While regional curves display patterns and relationships of channel form under varying hydrologic, climatic, geologic, and biologic conditions, the root drivers of channel form and profile are still widely disputed. Many studies have attempted to isolate the most important factors controlling channel dimensions and, although positive correlations have been made, it is undoubtedly a complex combination of many factors. Regional curves do not attempt to explain the complex interrelationships between all controlling variables, instead they merely present the results of how these factors contribute to a rivers final dimensions.

The purpose for the development of regional curves is to aid in calculating bankfull dimensions of width, depth, cross-sectional area, and discharge. Regional curves are created using data collected on natural, stable streams that are not actively aggrading or degrading. These relationships can then be transposed to streams degraded by human influence during restoration efforts. Given that regional curves do not explicitly provide knowledge on the root causes of river form and only present the results of the complex interrelations between many underlying factors, regional curves should only be used to predict channel dimensions in the same physiographic region for which they were developed. Even within a single physiographic region, regional curves exhibit high uncertainty and extreme caution should be used when using predicted dimensions for restoration.

Regional curves have been developed for many physiographic regions across the country, however, the amount of effort required to gain complete coverage of all physiographic regions and sub regions would be immense. Therefore, it is proposed that much value would be gained from the development of synthetic regional curves that could fill geographic gaps in existing regional curve coverage area. A stream restoration engineer in Colorado, David Bidelspach, has had success creating regional curves by summarizing trends in existing regional curves combined with a new metric of average annual precipitation. He proposes a linear, positive correlation between average annual precipitation and the y-intercept of existing regional curves. Therefore, the y-intercept is directly correlated with how the watershed responds to rainfall. Bidelspach refers to this theory as the Watershed Response Factor. He has investigated the Watershed Response Factor over the last few years and found many practical applications related to restoration engineering, specifically, to add in field identification of bankfull stage.

The primary purpose of this study is to test the Watershed Response Factor at a larger scale by applying the theory to a greater sample size of published regional curves. For this study, 48 published regional curve data sets were analyzed to determine the Watershed Response Factor equation for comparison to Bidelspach's independent research.

The Watershed Response Factor theory predicts that the exponent, or slope of the regression line, is similar enough between regional curves that an average, single slope value sufficiently represents all regional curves and can be applied to the synthetic regional curves developed from the watershed response factor. To eliminate this assumption, it seemed valuable to develop these synthetic regional curves in a way in which the y-intercept and slope of the regression line were both allowed to vary. Therefore, a second deliverable of this research is the creation of Rainfall-Based Regional Curves which categorize existing data based on rainfall values but allows the slope to also vary as a function of the best fit to the data.

This research requires data to be converted to geographically accurate shapefiles for spatial processing of watershed-averaged rainfall values. This provides a useful tool for people interested in regional curves because it offers the largest collection of regional curves known to date with the added benefit of geographically relevant shapes of coverage areas. The information in shapefile format can be viewed in any GIS software such as ArcGIS Pro or Google Earth Pro. Furthermore, the shapefiles provide valuable summary information such as regression equations and reference information.

Synthetic regional curves produced with the Watershed Response Factor and Rainfall-Based Regional Curve methodologies are not intended to replace regional curves and are not expected to be more accurate than regional curves, however, acceptance of these methodologies will hopefully reduce the need for the continual development of new regional curves. It is generally accepted that regional curves are not accurate enough to produce final-design channel dimensions during restoration projects which means that a slight reduction in the accuracy of synthetic region curves would not substantially impact the field of study. Acceptance of synthetic regional curves will hopefully shift resources away from regional curve studies and towards other research that aims to further understand the complex, physical processes behind river morphology.

BACKGROUND

Hydraulic geometry relationships and regional curves use measurable data collected on a representative sample of streams to predict the same information on other streams with similar characteristics. Ideally, the data is collected on natural, stable streams that are not actively aggrading or degrading. These relationships provide a quantifiable comparison between streams which can be used to guide restoration efforts. Regional curves are widely used by engineers to restore streams degraded by human influence to a more natural, stable state.

Hydraulic Geometry Relationships

Hydraulic geometry refers to stream channel dimensions such as width, depth, cross-sectional area, as well as hydraulic characteristics of velocity and sediment load, that help determine the shape of natural rivers (Leopold and Maddock 1953). Leopold and Maddock (1953) developed the foundational theory of stream channel hydraulic geometry by modeling interrelationships of hydraulic characteristics and how they vary with discharge by using simple power functions in the form demonstrated by **Equation 1**.

$$Y = aX^b \qquad \textbf{Equation 1}$$

Where a represents the y-intercept, b represents the slope, X is the independent variable of discharge, and Y is the dependent variable of width, depth, mean velocity, or suspended-sediment load. Hydraulic geometry relationships aim to quantify variables that correspond to the flows most important in forming the overall shape of the channel.

Channel-Forming Flows

Channel-forming flows are thought to be most important in shaping overall dimensions, form, and profile of a natural stream channel in a stable system. Bankfull, effective, and dominant discharge are terms describing different ways of quantifying channel-forming flows. Dominant discharge is qualitatively the discharge that, if maintained indefinitely, would reproduce the same channel geometry as the natural flow regime (Blench 1951; FISRWG 1998; Copeland et al. 2000). Effective discharge is the flow responsible for transporting the bulk amount of sediment over time, and is calculated by taking the product of the flow duration curve and sediment rating curve (Wolman and Miller 1960; Andrews 1980). Effective discharge is often difficult to obtain because it requires field measurements of sediment transport rates over a wide range of flows. Lastly, bankfull discharge is the flow that fills a natural, stable channel to the active floodplain elevation (Wolman and Leopold 1957; Williams 1978; Andrews 1980) and repre sents the breakpoint between channel-forming processes and floodplain forming processes (Copeland et al. 2000).

Studies have shown that bankfull, effective, and dominant discharge are similar in magnitude (Wolman and Miller 1960; Andrews 1980; Emmett and Wolman 2001). Therefore, bankfull discharge is often chosen for estimating channel-forming flow due to the relative ease of field identifying bankfull features. Each of these methods represent slightly different processes, so it is often best to use a combination of methods to accurately determine channel-forming discharge (Copeland et al. 2000). Dominant discharge is mostly theoretical and, thus, not practical to consider for most applications. Therefore, effective and bankfull discharges are most commonly used as channel-forming discharges (Andrews 1980; Emmett and Wolman 2001).

Bankfull Discharge

Bankfull discharge is the flow that fills a natural, stable channel to the elevation of the active floodplain (Williams, 1978; Andrews, 1980; Copeland *et al.*, 2000; Radecki-Pawlik, 2002). It represents the breakpoint between channel-forming processes and floodplain-forming processes (Copeland *et al.* 2000). Over the years, there have been many definitions of bankfull as well as numerous ways to identify bankfull stage and discharge. Each method has potential for errors and subjectivity related to the personal responsible for interpreting the data. Therefore, Radecki-Pawlik (2002) suggests using multiple methods to identify bankfull stage and associated discharge. Furthermore, he offers that bankfull discharge be reported as a range rather than a specific value as to acknowledge uncertainty in identification and calculations. Copeland et al (2000) also recommends identifying bankfull over a reach of at least one meander wavelength or as long as 10 channel widths, as opposed to the identification at a single cross-section.

For non-incised channels, Wolman (1955) describes bankfull stage as the elevation at which overbank flooding occurs. This can be determined by plotting the width-depth ratio against stage. Bankfull stage will be where the curve breaks sharply and the width becomes exceedingly large (Wolman 1955). Pickup and Warner (1976) recognize, however, that channels may become incised, in which case bankfull stage is actually lower than the elevation described by Wolman (1955). Leopold and Skibitzke (1967) offer various bankfull indicators such as lower limit of moss, lichens, herbs, and forbs; upper limit of sand deposits within shore boulders; and flood debris observed to coincide with the previously mentioned features. Woodyer (1968) identifies bankfull stage at the front edge of the depositional surface adjacent to the stream channel. He also relates the “middle” bench with bankfull stage. Williams (1978) uses a plot of cross-section al area verses top width to identify bankfull stage. Riley (1972) identifies bankfull stage as the first maximum of the “Riley Bench Index”. Wolman and Leopold (1957) considers the floodplain as the average of the highest elevation of channel bars and the top of cut banks into the existing floodplain. Dunne and Leopold (1978) define bankfull stage as corresponding to “the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or reforming bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels."

Wolman and Miller (1960) have found bankfull discharge to be equaled or exceeded every year or every other year. They believe the overall form of the river is determined largely by discharge approximating bankfull stage. Ackers and Charlton (1970) also attribute the characteristic meander length to bankfull flow. Conversely, Benson and Thomas (1966) believe the most dominant channel forming discharge for most rivers is much less than bankfull stage. Pickup and Warner (1976) have determined that bankfull discharge is of insufficient magnitude to determine the overall form of the river for streams with highly cohesive channel banks. They hypothesize that larger flows are necessary to erode banks and set the basic shape of the channel, whereas more frequent flows resembling bankfull discharge will transport the most sediment and determine the dominant shape of the channel bed within the confines of the banks. Schumm (1960) also relates channel dimensions to bank cohesiveness. If bank soil is highly cohesive (i.e., large percent of silt-clay), the channel will be deeper and narrower. If the bank soil is less cohesive, the channel will be shallower and wider (Schumm 1960). Mackin (1948), perhaps, was the first to propose a critical degree of erodibility of bank material. He suggests that channels less erodible than the critical degree will eventually develop a cross-section that maximizes sediment transport. Whereas streams more prone to erosion than the critical degree will become wider and shallower than the ideal transport section. Harvey (1969) determined that frequency and duration of bankfull conditions depend on flow regime when comparing small, low variability baseflow dominated regimes, to flashy, high flood peak regimes. Of the latter flow regime, he determined bankfull channel dimensions were adjusted to flows approximately equal to the annual flood. Low variability baseflow streams, however, exhibit channel dimensions adjusted to larger, less frequent events because the annual flood may not be competent to erode bed and banks (Harvey 1969). He also states that large, rarer flows last much longer for baseflow streams, allowing larger channel dimensions to be developed and maintained.

Hydraulic Geometry Summary

Geomorphology is the study of the formation, alteration, and configuration of landforms and their relationship with underlying structures. Fluvial Geomorphology is a sub-discipline of geomorphology that specifically seeks to understand riverine processes and how river channels form and change over time in response to both natural and human induced changes to the river corridor and its watershed. Leopold and Maddock (1953) were among the first to describe fluvial geomorphology quantitatively. They proposed that physical characteristics of streams such as width, depth, velocity, and discharge are all interconnected (Leopold and Maddock 1953). Hydraulic Geometry is a term developed to describe how geometric characteristics of a stream channel changes with distance downstream. Leopold and Maddock (1953) studied data collected over a period of 70 years to define a relationship where, if frequency of discharge remains constant at different points along a river, flow velocity, width, and depth increase non-linearly with discharge downstream. They empirically developed equations in the form of power functions to describe how velocity, width, and depth increase with discharge as seen in the following equations.

$w = cQ^e$ **Equation 2**

$d = fQ^g$ **Equation 3**

$v = hQ^i$ **Equation 4**

Variables w, d, and v are the bankfull parameters of width, depth, and velocity, respectively. The coefficients c, f, and h are y-intercepts of the regression line, and the exponents e, g, and i are slopes of the regression lines.

Channel slope tends to decrease with distance downstream. Therefore, Leopold and Maddock (1953) attribute the increase in velocity downstream to the fact that depth tends to overcompensate for the decrease in slope. Leopold and Maddock (1953) suggest that an average river system develops in a way to produce an equilibrium between the channel dimensions, water, and sediment transported. They believe that slope of the hydraulic geometry equations is the hydraulic factor which makes the final adjustment over time to maintain or reach a state of quasi-equilibrium.

Although hydraulic geometry relationships provide a useful tool to predict channel dimensions as a function of bankfull discharge, calculating discharge can be difficult for ungagged streams and relies on methods such as regressions curves, hydraulic models, and flow equations (e.g., Manning's equation) that add uncertainty and complexity to the analysis. For this reason, regional curves became popular because they predict channel dimensions using drainage area instead of discharge.

Regional Curves

Dunne and Leopold (1978) were the first to observe that a relationship exists between bankfull channel dimensions and drainage area. They determined that simple power functions such as the hydraulic geometry equations developed by Leopold and Maddock (1953) could also relate bankfull channel dimensions to drainage area for watersheds within the same physiographic region. Plots of these relationships became known as regional curves. Regression equations created from these plots are presented in the form of **Equation 5**; where DA is drainage area in square miles, k is the slope of the regression line, j is the y-intercept of the regression line, and X is the bankfull characteristic of width, depth, or cross-sectional area.

$$X = jDA^k \quad \textbf{Equation 5}$$

Physiographic region refers to areas that exhibit similar physical characteristics, which are shaped by a combination of climate, underlying geology, and geologic history. Fenneman and Johnson (1946) developed a map of eight major physiographic regions of the United States. The eight regions are the: Appalachian Highlands, Atlantic Plain, Interior Highlands, Interior Plains, Intermontane Plains, Laurentian Plateaus, Pacific Mountain System, and Rocky Mountain System. Additionally, the map sub-divides those eight regions into 25 sub-regions (Figure 1) referred to as provinces, as well as 86 sections, which represent areas of unique topography, geology, and geomorphic history. When regional curve studies group data into physiographic regions, they are often referring to sub-regions, or provinces, as defined by Fenneman and Johnson (1946).

Figure 1. Physiographic Map of the United States (Fenneman and Johnson 1946)

Since 1978, a large effort has been underway to gather data and develop regional curves throughout the country. The purpose for the development of regional curves is to aid in calculating bankfull dimensions where bankfull features are difficult to identify. These dimensions are then used for natural channel design during stream restoration projects.

Regional curves are developed empirically using bankfull measurements collected during a field survey. Bankfull measurements are influenced by a multitude of factors such as underlying geology, soil type, watershed land use, vegetation type and coverage, topographic relief, rainfall-runoff interactions, freeze-thaw cycles, temperature, and snowfall, to name a few. Hydraulic geometry relationships and regional curves capture the result of how all these factors influence the final geometric characteristics of the stream, however, it is not fully understood how each one of these factors influence the stream on an individual basis.

Studies have examined the effects of urbanization on channel dimensions. Hammer (1972) found that connected storm sewer systems and large impervious areas (> 1 acre) result in the largest increase in channel size for urban streams near Philadelphia, Pennsylvania. Hammer (1972) also concludes that the impact of imperviousness is greater in watersheds with higher topographic relief (i.e., channel slope and land area slope). Doll et. al. (2002) examined urban and suburban streams in the Piedmont region of North Carolina with watersheds that had greater than 10 percent imperviousness. They found a substantial increase in bankfull cross-sectional area, width, and depth compared to a study on rural streams in the same region (Harman et al. 1999).

Limitations of Regional Curves

Although regional curves can be a good starting point in the absence of other data, there are limitations restricting their use for final design channel dimensions. Regional curves are plotted on a log scale and, although the fitted curve displays a relatively low error ($r^2 > 0.8$), data points often fall within 20 – 500 percent of the curve. Figure 2 is a regional curve developed for streams in Massachusetts. Although the r^2 value is 0.911, the data still exhibits a large degree a variability for some values of drainage area. For example, for a drainage area of 40 square miles, values of bankfull cross-sectional area range from 100 to 300 square feet. This large variation in data is often attributed to the difficulty and subjectivity related to identifying bankfull stage. Additionally, regional curve studies usually encompass a large geographic area with varying hydrological, geological, or biological conditions that effect rainfall-runoff processes. Additional error is attributed to collecting data from streams when their flow regime is unnaturally altered by anthropogenic influences. Activities such as damming, water diversions, and groundwater pumping can result in lower peak flows of shorter duration and often result in disproportionally small bankfull channel area relative to drainage area. Alternatively, urbanization and added imperviousness often lead to increased flows that promote a larger bankfull channel relative to drainage area.

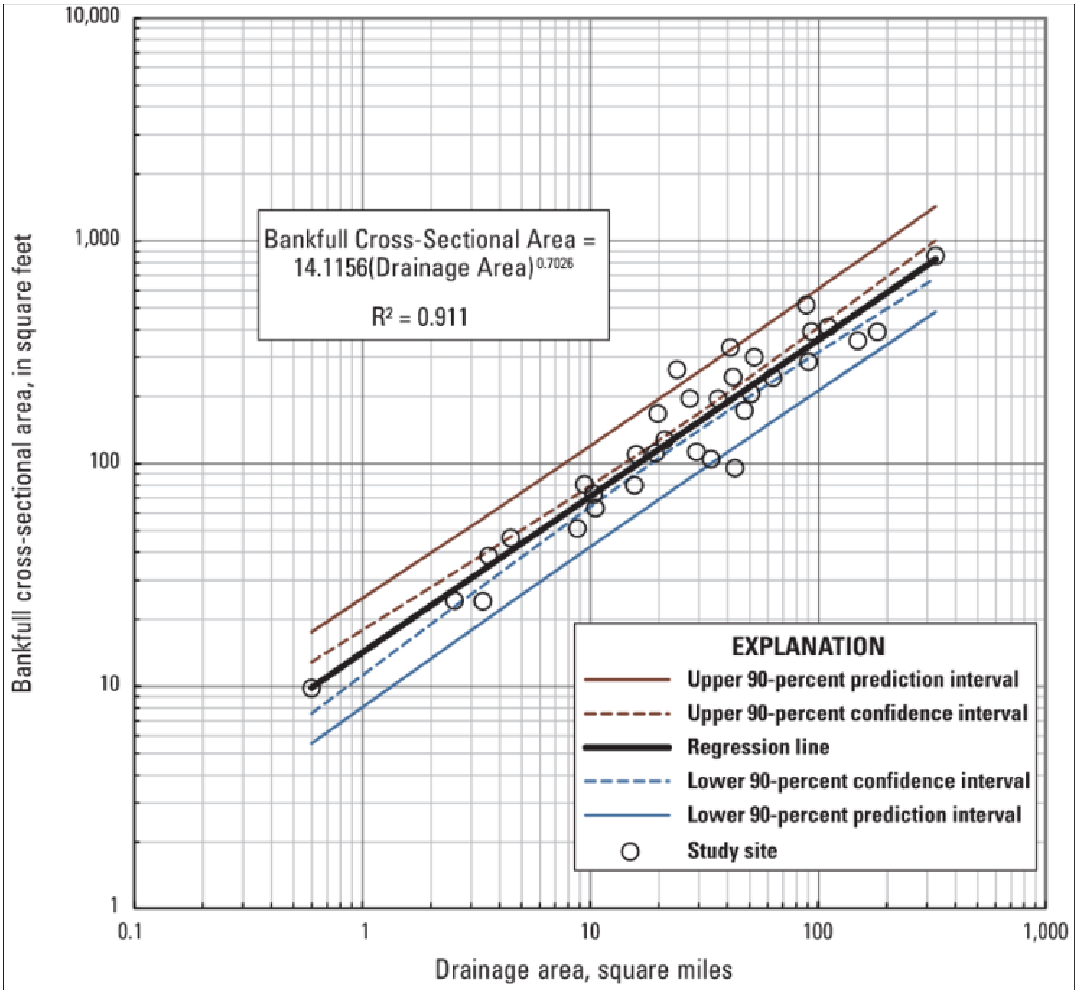


Figure 2. Regional curve developed by Bent and Waite (2013) for steams in Massachusetts

Regional Curve Summary

Many regional curves have been created to relate bankfull channel dimensions with watershed drainage area within a specific physiographic province. However, most studies only represent part of each province and do not represent the entire physiographic province (Johnson and Fecko 2008). Johnson and Fecko (2008) compared regional curves to determine whether regional equations are statistically different within a single province, and different between provinces. The results of their study concluded that the majority of regional equations are statistically similar within their respective physiographic province. They also found the regional equations for the Appalachian Plateau, New England, and Valley and Ridge provinces to be statistically similar. However, they found equations for the Piedmont, Coastal Plain, and Blue Ridge provinces to be statistically different. Additionally, Johnson and Fecko (2008) found equation for width to be statistically different within the Piedmont region. Equations in the Piedmont region by Doll et al. (2002) studying urban watersheds, and equations by Cinotto (2003) which included sites with kars(Johnson and

Fecko 2008). Although statistical similarities were found within certain physiographic regions, as well as between some physiographic provinces, Johnson and Fecko (2008) believe there exists enough statistical differences to warrant the development of regional curves for each specific province.

Johnson and Fecko (2008) also found statistical differences between equations developed in the Coastal region of northern Florida. Metcalf et. al. (2009) recognized the differences in the northern Florida curves and separated the curves. The study divided northern Florida into two hydro-physiographic regions based on rainfall-runoff values. The North Florida Coastal Plain (NFCP) region was defined by rainfall-runoff values of 8-18 inches per year, and the Northwest Florida Coastal Plain (NWFCP) region was defined by rainfall-runoff values of 18-40 inches per year. Mean annual rainfall for the two regions ranges from 52-56 inches for the NFCP and 52-64 inches for the NWFCP. Despite similar annual rainfall totals between the two regions, the study concluded that there is a direct relationship between mean annual runoff and bankfull discharge. Like discharge, the NWFCP regional curve predicted bankfull cross-sectional areas that were two to three times larger than NFCP regional curve.

Watershed Response Factor

Watershed Response Factor (WRF) is a new concept related to regional curves. As described by **Equation 5**, $X = j*DA^k$ is the typical form of the regression equation created from a single-variable regional curve. For the purpose of developing the WRF, X will be analyzed primarily representing bankfull cross-sectional area (XS_Area). In **Equation 5**, the exponent k is the slope of the regression equation and j is the y-intercept.

Development of the WRF concept is attributed to David Bidelspach, a stream restoration engineer residing in Livermore, Colorado. Bidelspach has built his career in stream restoration where he implements concepts and techniques overlapping Rosgen's Natural Channel Design curriculum. Like Rosgen, use of regional curves is at the forefront of Bidelspach design process; however, he recognizes a high degree of uncertainty and a large range in possible outcomes when using published regional curves.

Although much uncertainty is observed in published regional curves, a great deal of resources (primarily by government agencies) is expended each year to develop new regional curves across the nation. For this reason, among others, Bidelspach has been promoting the WRF as a tool to supplement existing regional curves to reduce the need for continual development of additional regional curves.

Through Bidelspach's work using regional curves, he observed a correlation between the y-intercept of the regression line and average annual rainfall of the watershed. Therefore, he predicts the y-intercept value to be a good metric of how the watershed responds to rainfall. Consequently, he refers to the y-intercept as the Watershed Response Factor.

Furthermore, he predicts that the slope of any regional curve regression line can be approximated using an average slope value of 0.67. Substituting this methodology into **Equation 5** produces an estimation of bankfull cross-sectional area (**Equation 6**) using an easily accessible variable of drainage area (DA) and only one unknown variable (WRF).

$$XS\ Area = WRF * DA^{0.67}$$ **Equation 6**

Bidelspach predicts a linear correlation between the WRF and average annual rainfall in inches per year. Therefore, plotting the y-intercept of existing regional curves against corresponding average annual rainfall can be summarized by a linear regression line and associated equation which can be used to predict the WRF for any value of average annual rainfall (Figure 3). Bidelspach's work in plotting regional curve y-intercept values against average annual rainfall (AAR) has produced **Equation 7**.

$$WRF = 1.5 + 0.34 * AAR$$ **Equation 7**

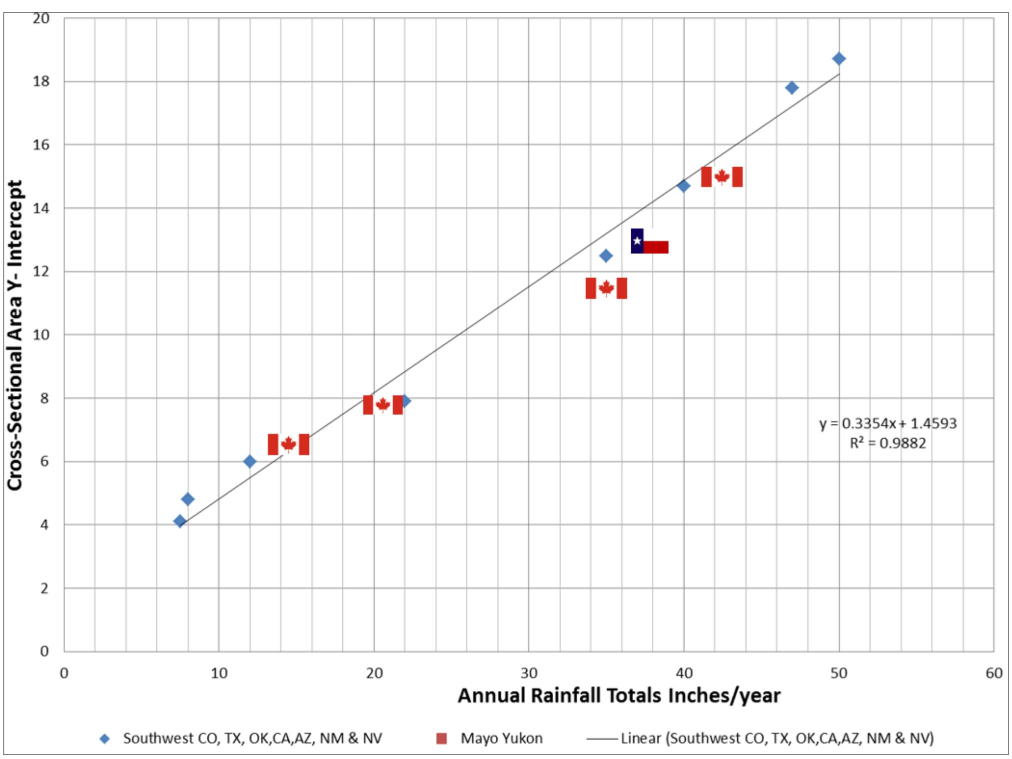


Figure 3. Bidelspach work in developing the WRF

The Watershed Response Factor becomes a powerful tool because it enables a prediction of bankfull cross-section area for any stream in the U.S. (and other countries with similar physiographic characteristics) through a quick and simple desktop analysis. To use this tool, simply use any number of computer applications such as GIS or USGS's StreamStats to delineate a watershed and obtain the drainage area and average annual rainfall. Then use **Equation 7** to calculate the WRF followed by **Equation 6** to produce and estimate of bankfull cross-sectional area.

The Watershed Response Factor is a valuable tool for initial estimation of bankfull cross-sectional area and can help identify bankfull stage during a field investigation, however, it should be noted that it is not intended to produce engineering design dimensions. The expected error associated with this methodology is consistent with the large-scale regional curves used to produce the WRF. It is recommended to use the WRF when a project is outside the coverage of an existing, published regional curve. Existing regional curves and the WRF should then only be used in preliminary design and to help inform a field investigation to aid in creating a local, project-specific mini regional curve. Additionally, when collecting data for a mini regional curve, it is also beneficial to obtain other geomorphic channel features such as inner berm area and bankfull mean depth and width.

ANALYSIS

There have been many regional curve studies published across the country. As mentioned above, studies have compared regional curves to determine whether regional equations are statistically different within a single province, or different between provinces. Some regional equations were found to be statistically similar to others within the same province, or across provinces. Although some physiographic regions were found to produce similar regional curves, Johnson and Fecko (2008) believe there are still enough differences to warrant the development of regional curves across each physiographic region.

Although physiographic sub-regions, or provinces, seem like a very logical way in which to classify data during regional curve studies, there still appears to be a large degree of variability in the data within each province as observed by low coefficients of determination (r-squared) values of some curves. Existing studies have attributed variability in bankfull dimensions to urbanization and associated added imperviousness to the watershed. Another study attributed differences in regression equations to rainfall-runoff dynamics.

It is hypothesized herein that average annual rainfall plays an important role in determining the geometric characteristics of a stream as quantified in the context of regional curve equations by the y-intercept and slope of the regression line. The primary goal of this project is to implement a new concept referred to as Watershed Response Factor (WRF) and apply it to existing, published regional curves. Additionally, a new set of modified regional curves will be developed and referred to as Rainfall-Based Regional Curves. The new curves group data by watershed mean annual rainfall instead of region (or province) as used by traditional regional curve studies.

The secondary goal of this project is to provide access to the datasets created for this project in hopes that it will help other researchers further explore this area of study. Among the available datasets, a shapefile has been created in ESRI shapefile and Google Earth Pro formats that allows users to graphically locate existing regional curve studies with geographically accurate shapes covering each regional curve study extents, along with each stream measurement point that makes up the studies. This is intended to help practitioners quickly locate and utilize existing regional curve studies across the country.

Data Collection

Selection Criteria

This study uses a compilation of existing, published regional curves across the nation. Given the goals of this project, it was necessary to geographically locate the data provided in the existing regional curve studies. This created two criteria necessary to determine if an existing regional curve could be implemented into this analysis. One, the regional curve study must provide the data, in tabular format, used to create the regional curve equation. Two, the data must either include latitude and longitude information for each data point or provide a USGS gage number for which the coordinates can be joined from other data sets.

Regional curves began to be developed in the late 1970s and are sometimes hard to track down given that there is no single source that lists all published regional curves. Therefore, the total number of published regional curves could not be determined; however, 46 studies were discovered during this study. Of the 46 studies, 38 met the criteria listed above. Given that some studies produced multiple curves/equations, the 38 studies used for this analysis produced a total of 48 regional equations and accompanying data sets.

Implementation

Once an existing regional curve study was determined to fit the selection criteria, data was transferred from the study into an Excel database. The most relevant information included latitude, longitude, USGS gage number (where applicable), drainage area, bankfull cross-sectional area, width, depth, and discharge. Given that the secondary goal of this project was to provide a usable dataset to facilitate future research, additional information was also collected such as bankfull discharge recurrence interval, sediment size, Rosgen classification, etc. Not all existing studies published the same set of attributes for the data collected. Therefore, a standard attribute table was created in Excel and data was entered for each curve where available. Table 1 shows the 26 attributes in the standard table. An example standard table with associated data is included in Appendix A.

Table 1. Standard Attribute Table

Number	Attribute	Number	Attribute
1	Curve ID	14	Bankfull Max Depth (ft)
2	Reference	15	Bankfull Velocity (ft/s)
3	Notes	16	Bankfull Discharge (ft^3/s)
4	Latitude	17	Return Period (years)
5	Longitude	18	Channel Slope (ft/ft)
6	USGS Gage Number	19	Sinuosity
7	Ungaged Number	20	Width/Mean Depth Ratio
8	Site Name	21	Flood Prone Width (ft)
9	Site Number	22	Entrenchment Ratio
10	Drainage Area (mi^2)	23	Rosgen Classification
11	Bankfull Cross-Sectional Area (ft^2)	24	Grain Size d_{10} (mm)
12	Bankfull Width (ft)	25	Grain Size d_{50} (mm)
13	Bankfull Mean Depth (ft)	26	Grain Size d_{84} (mm)

In addition to the attributes in Table 1, a summary table was created to summarize the regional curve equations and is presented in Appendix A. The summary table displays the specific curve ID assigned to each curve/equation set for the purposes of this study. The summary table also displays the regional curve reference, minimum and maximum drainage area, and bankfull equations of cross-sectional area, width, depth, and discharge. The bankfull equation section shows the full equation along with the y-intercept, exponent, and r-squared values of the curves. Table 2 shows an excerpt of Appendix A to quickly reference the curve ID and publication reference.

Table 2. Regional curve ID and reference

Number	Curve ID	Reference	Number	Curve ID	Reference
1	AL_1	(Brantley 2016b)	25	NC_1	(Harman et al. 2000)
2	AL_2	(Brantley 2016a)	26	NC_2	(Harman et al. 1999)
3	AL_3	(Metcalf 2005)	27	NC_3	(Doll et al. 2003)
4	AR_1	(Pugh and Redman 2019)	28	NC_4a	(Doll et al. 2002)
5	AZ_1	(Moody et al. 2003)	29	NC_4b	(Doll et al. 2002)
6	CO_1	(Elliott and Cartier 1986)	30	NC_5	(Sweet and Geratz 2003)
7	CO_2a	(Yochum 2003)	31	NM_1	(Moody et al. 2003)
8	CO_2b	(Yochum 2003)	32	NY_1	(Mulvihill et al. 2007)
9	CO_2c	(Yochum 2003)	33	NY_2	(Mulvihill and Baldigo 2007)
10	FL_1	(Metcalf 2004)	34	NY_3	(Miller and Davis 2003)
11	FL_2	(Metcalf 2004)	35	NY_4	(Miller and Davis 2003)
12	FL_3a	(Metcalf et al. 2009)	36	NY_5	(Westergard et al. 2004)
13	FL_3b	(Metcalf et al. 2009)	37	NY_6	(Mulvihill et al. 2005)
14	ID_1	(Castro and Jackson 2001)	38	NY_7	(Mulvihill et al. 2005)
15	ID_2	(Emmett 1975)	39	OH_1a	(Sherwood and Huitger 2005)
16	IN_1a	(Robinson 2013)	40	OH_1b	(Sherwood and Huitger 2005)
17	IN_1b	(Robinson 2013)	41	PA_1	(White 2001)
18	IN_1c	(Robinson 2013)	42	PA_2	(Cinotto 2003)
19	MA_1	(Bent and Waite 2013)	43	PA_3a	(Chaplin 2005)
20	MD_1	(McCandless and Everett 2002)	44	PA_3b	(Chaplin 2005)
21	MD_2	(McCandless 2003a)	45	VA_1	(Keaton et al. 2005)
22	MD_3	(McCandless 2003b)	46	VA_2	(Lotspeich 2009)
23	MD_4	(Krstolic and Chaplin 2007)	47	WV_1	(Messinger 2009)
24	MI_1	(Rachol and Boley-Morse 2009)	48	WY_1	(Foster 2012)

Data Processing

Excel

Data from each of the 48 regional curves was copied into the standard table in Excel. A separate Excel sheet was created for each to help with data processing and organization. If the data included latitude and longitude coordinates, no further action was required. If no coordinate information was available but a USGS gage number was provided, a second dataset titled *Gages II* published by the U.S. Geologic Survey (Falcone 2011) was used to assign coordinate information. Some USGS gage numbers were not included the *Gages II* dataset and had to be manually obtained through the USGS website. Some studies included data for ungagged watersheds and, therefore, no USGS gage number was available. In this case, if enough information was provided in the report to determine an approximate location of the mea surement point, the coordinate information was manually determined using Google Maps or Google Earth Pro. For the remainder of the analysis, the USGS gage number was used as the primary key to identify each data point. For ungagged data points, a primary key was assigned to each data point in the form of "Curve ID_Number." An example of AL_2_8 would represent the 8th data point in the AL_2 curve.

RStudio Pre-Processing

Once data processing was complete in Excel, RStudio Version 1.3.1073 (R) was used to further process and investigate the data. Each Excel sheet was imported into R as data frames to produce 48 individual data frames. The data frames were joined together to produce a single data frame called "**All_Data**" which contained 1,333 data points. **All_Data** was sub-divided based on availability of coordinate information. Data with coordinate information was included into a second data frame called "**Geo_Data**" which contained 1,015 data points. "**Geo_Data**" was then converted from a data frame into a point shapefile using the included latitude and longitude information.

For this analysis, it was necessary to calculate the average annual rainfall for each data point. Rainfall at a single point along a stream may not provide an accurate representation of the overall hydrologic conditions so it was necessary to calculate the average rainfall across the entire contributing drainage basin. To do this, a watershed, or drainage basin, first needed to be associated with each data point. The *Gages II* database provided a polygon shapefile of drainage basins associated with 9,322 USGS gages. Another dataset titled "*USGS Streamgage NHDPlus Version 1 Basins 2011*" provided 18 polygon shapefiles of drainage basins associated with 19,031 USGS gages (USGS 2012). R was used to join the 19 total datasets together into a single polygon shapefile.

Ungagged sites, along with some gaged sites, were not included in the 19 existing USGS datasets. For this scenario, USGS StreamStats Version 4.6.2 (USGS 2016) application was used to manually calculate and download polygon shapefiles for each data point location, where available. Some states, however, have yet to develop StreamStats. Additionally, StreamStats does not return a drainage area if the watershed extends outside of the United States (i.e., Canada). States yet to implement StreamStats include Texas, Florida, Michigan, and Alaska.

ArcGIS Pro

ArcGIS Pro Version 2.6.2 was used to perform spatial geoprocessing tasks for this analysis. First, the large polygon shapefile of USGS basins, along with individual StreamStats basins, were joined to the

Geo_Data shapefile to produce a dataset titled "**All_Basins_Geo_Data**". Next, mean annual rainfall values were calculated for each drainage basin in **All_Basins_Geo_Data** using a raster file titled USA_Mean_Rainfall (USGS 2021) accessed through ArcGIS Pro online portal. The resulting dataset is called "**All_Basins_Geo_Data_Precip.**" The USA_Mean_Rainfall dataset was developed by the U.S. Geological Survey for the period of January 1971 through December 2009 as part of a larger study to develop climate indices, referred to as bioclimate predictors, which highlight climate conditions related to species physiology.

To support the secondary goals of this project, a polygon shapefile was created to display the regional curves with a geographically accurate shape of the combined drainage basins included in each curve. However, a shape was only created for the curves that had drainage basins identified. Additionally, some curves only had partial drainage basin coverage. Therefore, the shapes in this shapefile are intended to be used for reference only and should not be considered a complete dataset. The Summary Table shown in Appendix A was also imported into ArcGIS Pro and joined to this representative curve shapefile. This dataset can be viewed in GIS applications or Google Earth Pro to quickly locate regional curves and view summary data such as regression equations and publication reference.

Watershed Response Factor Development

An equation using the Watershed Response Factor has already been developed by David Bidelspach using a combination of published regional curves and unpublished mini regional curves as provided by **Equation 6** and **Equation 7**. This project applies the same methodology to the 48 published regional curves sampled for this analysis. **Equation 7** is replicated using the reported y-intercept values of the 48 published regional curves as well as basin-averaged annual rainfall values calculated in ArcGIS Pro for each representative regional curve shape. Additionally, WRF methodology assumes a slope of the regression line which has been predicted to be 0.67. This assumption is investigated by examining the spread of published regression slopes through summary statistics such a range, inner quartile range, mean, and median values.

Rainfall-Based Regional Curve Development

The dataset **All_Basins_Geo_Data_Precip** was imported back into R to perform the final analysis of this study. The dataset contained 741 data points to complete the final analysis for this study. The dataset was categorized according to ranges in average annual rainfall values. The data in each category was then graphed like a standard regional curve with drainage area on the x-axis and bankfull cross-sectional area on the y-axis. A regression equation was calculated for each rainfall category. The rainfall category for each curve was determined by trial and error based on data availability and r-squared values of the resulting regression equations. For this study, a total of eight trials were used to find the optimal rainfall ranges. The results for all eight trials are provided in Appendix B. A summary of the final rainfall categories and resulting regression equations are shown in Table 3. See results section of this report for final rainfall-based regional curves.

Table 3. Final rainfall categories

Rainfall Categories - Avg. Annual Rainfall (in)	Sample Size	Regression Slope	Regression Intercept	Regression Equation Bankfull Cross-Sectional Area	r-squared
All data	741	0.54	23.07	XS Area = 23.07*DA^0.54	0.74
15-30	61	0.67	3.64	XS Area = 3.64*DA^0.67	0.82
30-45	363	0.5	24.82	XS Area = 24.82*DA^0.5	0.74
45-55	191	0.61	23.45	XS Area = 23.45*DA^0.61	0.81
>55	126	0.66	23.96	XS Area = 23.96*DA^0.66	0.94

RESULTS AND DISCUSSION

Regional curves typically report regression equations for bankfull characteristics of cross-sectional area, width, depth, and discharge. Although this analysis could be performed for each bankfull characteristic, bankfull cross-sectional area is often the most useful during the design of restoration projects and is the primary focus for this study. The 48 regional curves investigated for this analysis produced a total of 1310 data points. Drainage area polygons were obtained or created for 741 of the 1310 data points. A regional curve of all 741 data points is shown in Figure 4 for reference only. An r-squared value of 0.74 may suggest the regression line provides a fair representation of the combined data; however, a closer look at the data shows an almost three-fold range of cross-sectional area values for any given drainage area (e.g. for drainage area of 12 sq. mi., cross-sectional area range is 9 – 500 sq. ft.). This large range of values illustrates the need to divide the data into categories of similar basin characteristics. Results and discussion in the following sections summarize the analysis related to the Watershed Response Factor, Rainfall-Based Regional Curves, and supplemental digital data created for practitioners or future researchers.

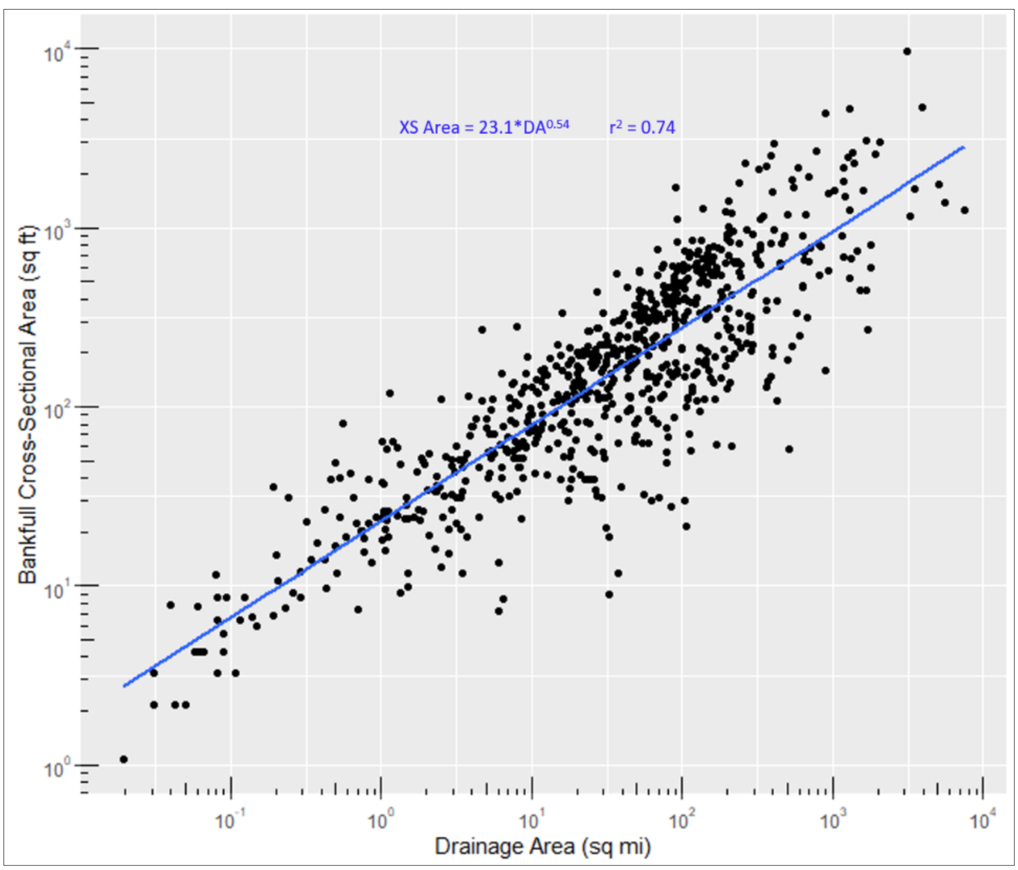


Figure 4. All data used for rainfall-based regional curves

Watershed Response Factor

Existing, published regional curves were analyzed to determine the Watershed Response Factor (WRF) in relation to bankfull cross-sectional area. A total of 48 regional curves were investigated for this project, however, two curves were developed as a multi-regression analysis and could not be used to develop the WRF. A map of the existing regional curves is provided in Appendix C and GIS data in shapefile format is included in Appendix D.

When implementing the WRF, it is first necessary to assume a slope of the regression line. For the 46 regional curves sampled, the slope of the regression lines varied from 0.21 to 0.99, however, most of the data fell between 0.64 and 0.74 with a mean and median slope of 0.68 and 0.69, respectively. The mean slope of 0.68 will be used as the representative slope for this analysis.

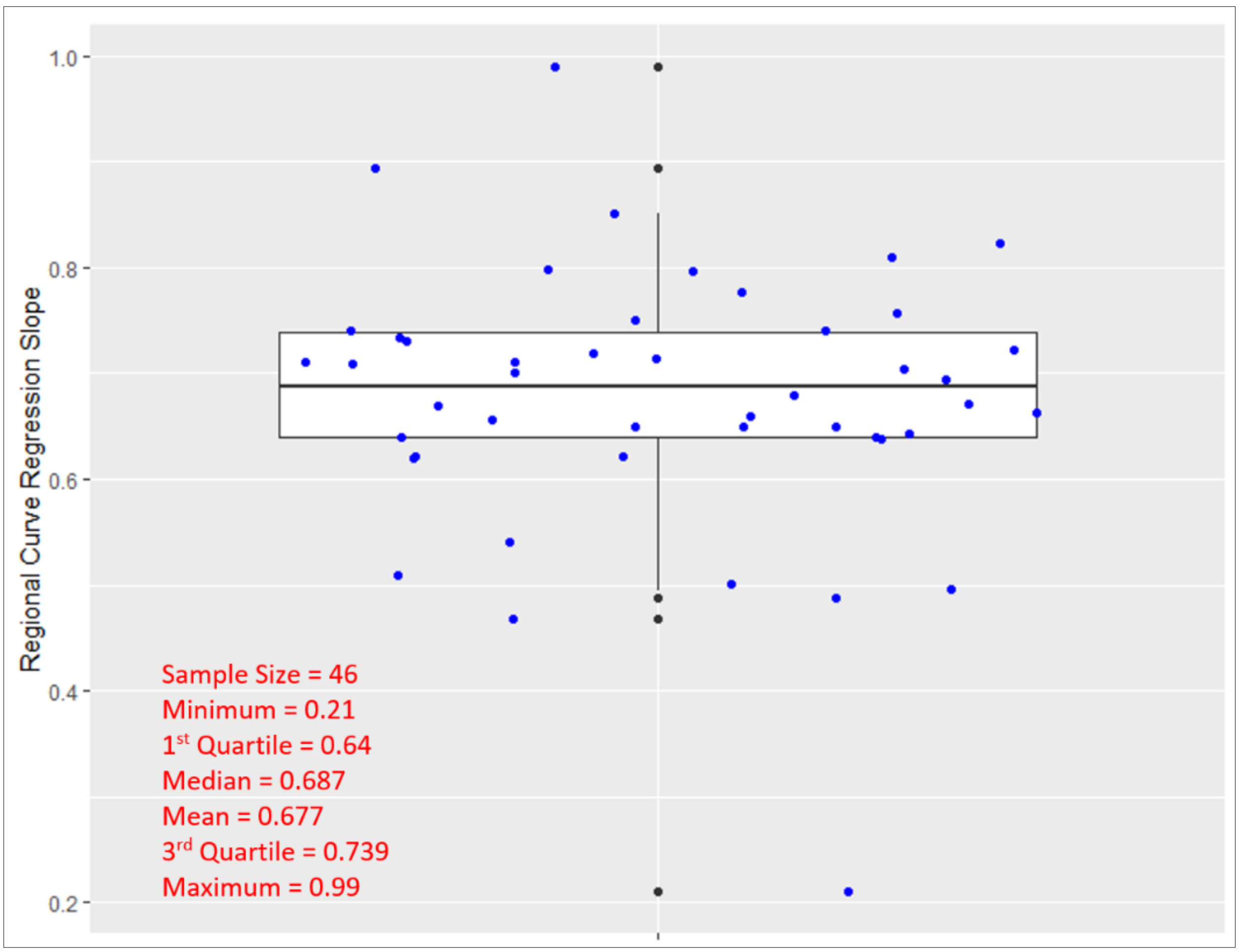


Figure 5. Existing regional curve regression slope distribution

The WRF is defined as the y-intercept (i.e. L in the following equation) of the regression equation in the form of XS_Area = L*DA$^{0.68}$ and is calculated using a linear regression equation produced by the graph of cross-sectional area as a function of average annual rainfall. A watershed averaged annual rainfall value is required to calculate the WRF. Therefore, only regional curves that provided geographical information could be used to develop the WRF. Of the 46 regional curves using a single regression analysis, 39 curves had enough information to create a representative watershed polygon. The remaining 7 curves utilized manually created polygons representing approximate study extents estimated from the regional curve reports. Average annual rainfall was then calculated for each polygon. Figure 6 shows the results of graphing the y-intercept of the regional curves against average annual rainfall (AAR). The y-intercept, or WRF, can then be calculated using **Equation 8**.

WRF = 3.3 + 0.31(AAR)* **Equation 8**

Examination of Figure 6 reveals 4 outliers in the graph. Removal of the outliers (Figure 7) increases the r-squared value from 0.08 to 0.22 and the resulting equation becomes:

WRF = 1.5 + 0.28(AAR)* **Equation 9**

The WRF equation produced from published regional curves (**Equation 9**) during this study is similar to **Equation 7** (*WRF = 1.5 + 0.34*AAR*) developed by David Bidelspach. Regional curves often exhibit a high degree of variability, as explained in preceeding sections, and shouldn't be used to develop final design parameters in engineering restoration projects. However, the WRF is a valuable tool to aid in field identifying bankfull stage in areas that lack a developed regional curves.

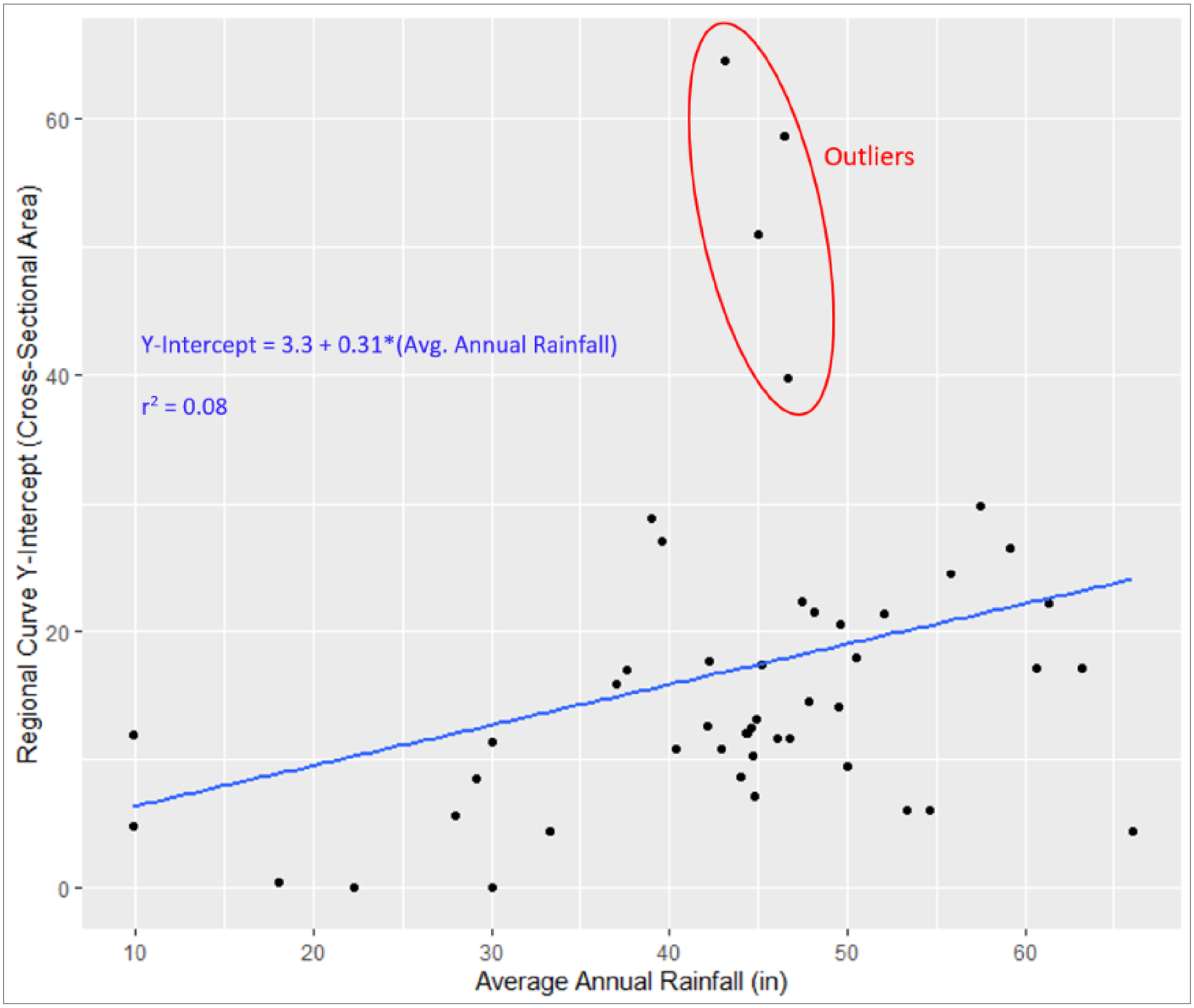


Figure 6. Watershed Response Factor

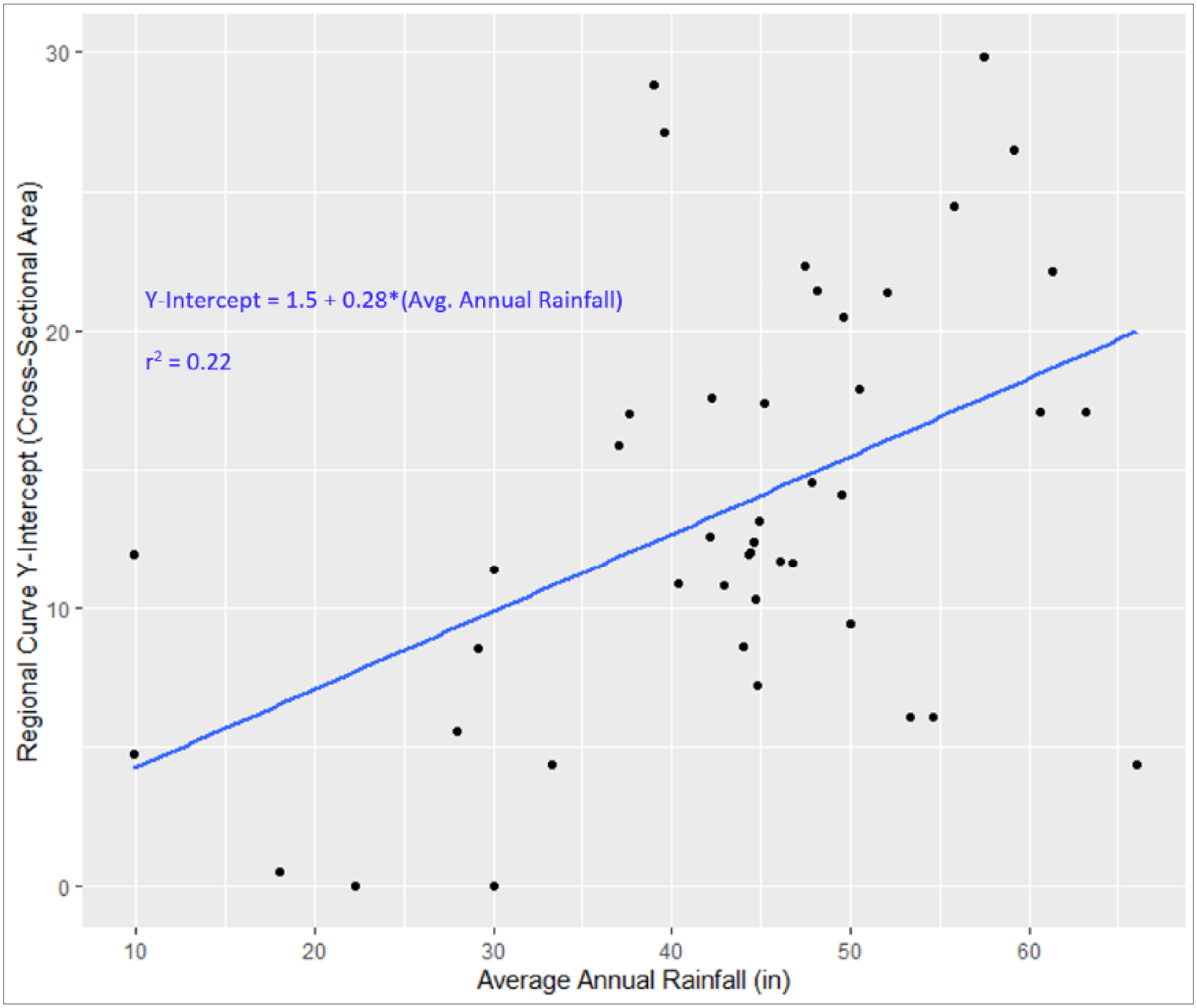


Figure 7. Watershed Response Factor (outliers removed)

Rainfall-Based Regional Curves

The main drawback with the Watershed Response Factor concept is that it requires an assumed slope of the regression equation. Figure 5 demonstrates a large range of slope values among published regional curves. Therefore, the concept of rainfall-based regional curves was developed. This method categorizes the data based on average annual rainfall and then creates a regional curve for each rainfall category (Figure 8). A regression line and associated equation is then created for each curve. Therefore, each curve exhibits a data-specific slope and y-intercept value.

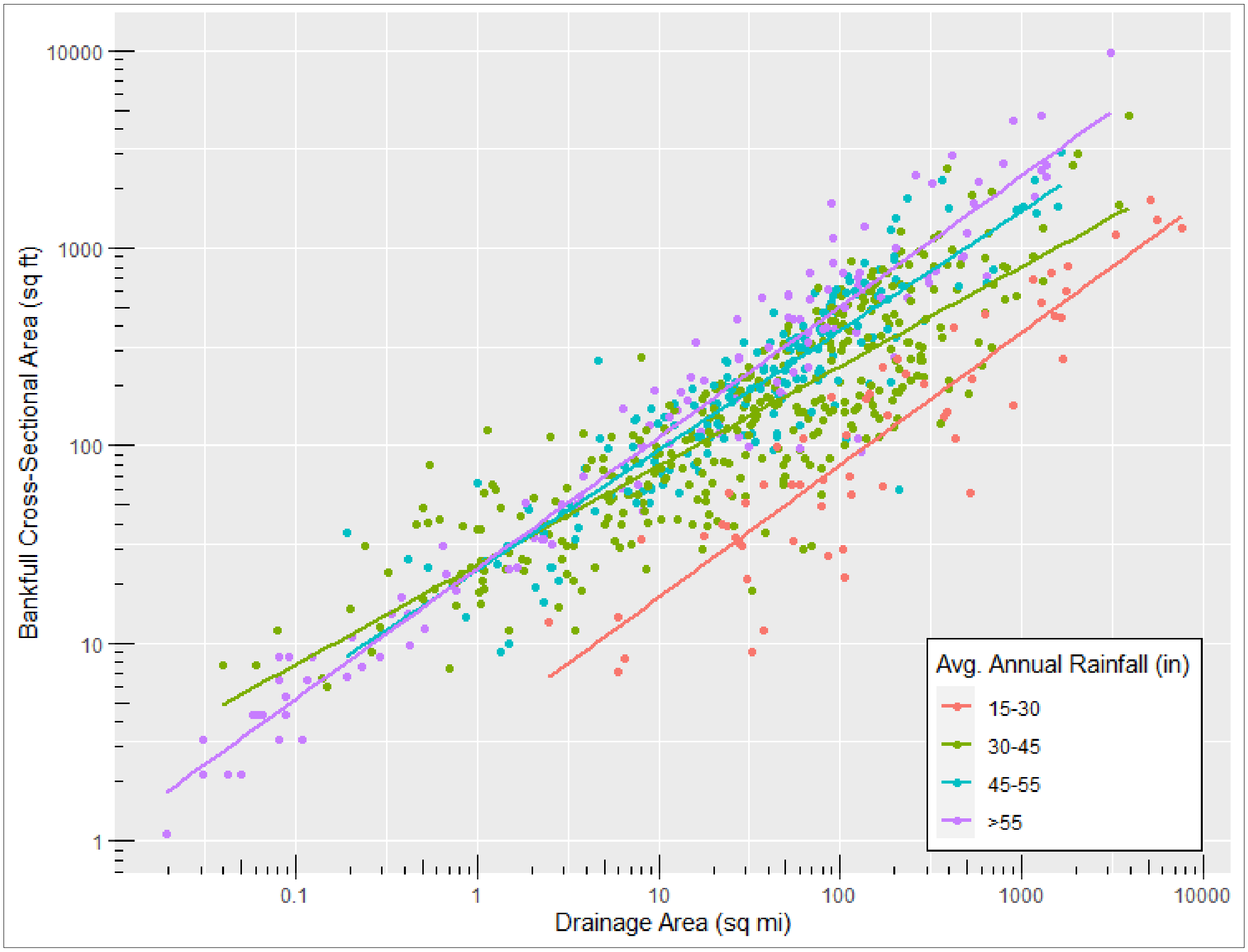


Figure 8. Rainfall-based regional curves with data points

Figure 8 shows a lot of overlap in data ranges between curves. The most significant contrast of data is between the lowest and highest rainfall curves (15-30 inches and >55 inches, respectively). This makes sense because hydrology is often considered the main process driver of fluvial systems because flowing water is the main force that imparts energy to the system (Castro and Thorne 2019). Although stream shape is ultimately determined through complex interactions between physical stream and watershed characteristics, hydrology is the sole process *driving* change, while aspects of geology and biology provide *resistance* to change (Castro and Thorne 2019).

Generally, with all other factors held constant, streams that receive less annual rainfall are expected to produce and maintain a smaller bankfull channel. For this analysis, all watersheds produced average annual rainfall values above 15 inches. Data suggests a stronger relative impact is observed on stream size when approaching the minimum rainfall values and less impact for areas of high annual rainfall.

Final rainfall-based regional curves with regression equations and r-squared values are provided in Figure 9. For the four curves, r-squared values range from 0.74 to 0.94. The 46 published regional curves have r-squared values ranging from 0.49-0.99; however, most of the curves exhibit r-squared values between 0.91 and 0.968 (1st and 3rd quartile), with mean and medium values of 0.915 and 0.948, respectively (Figure 10).

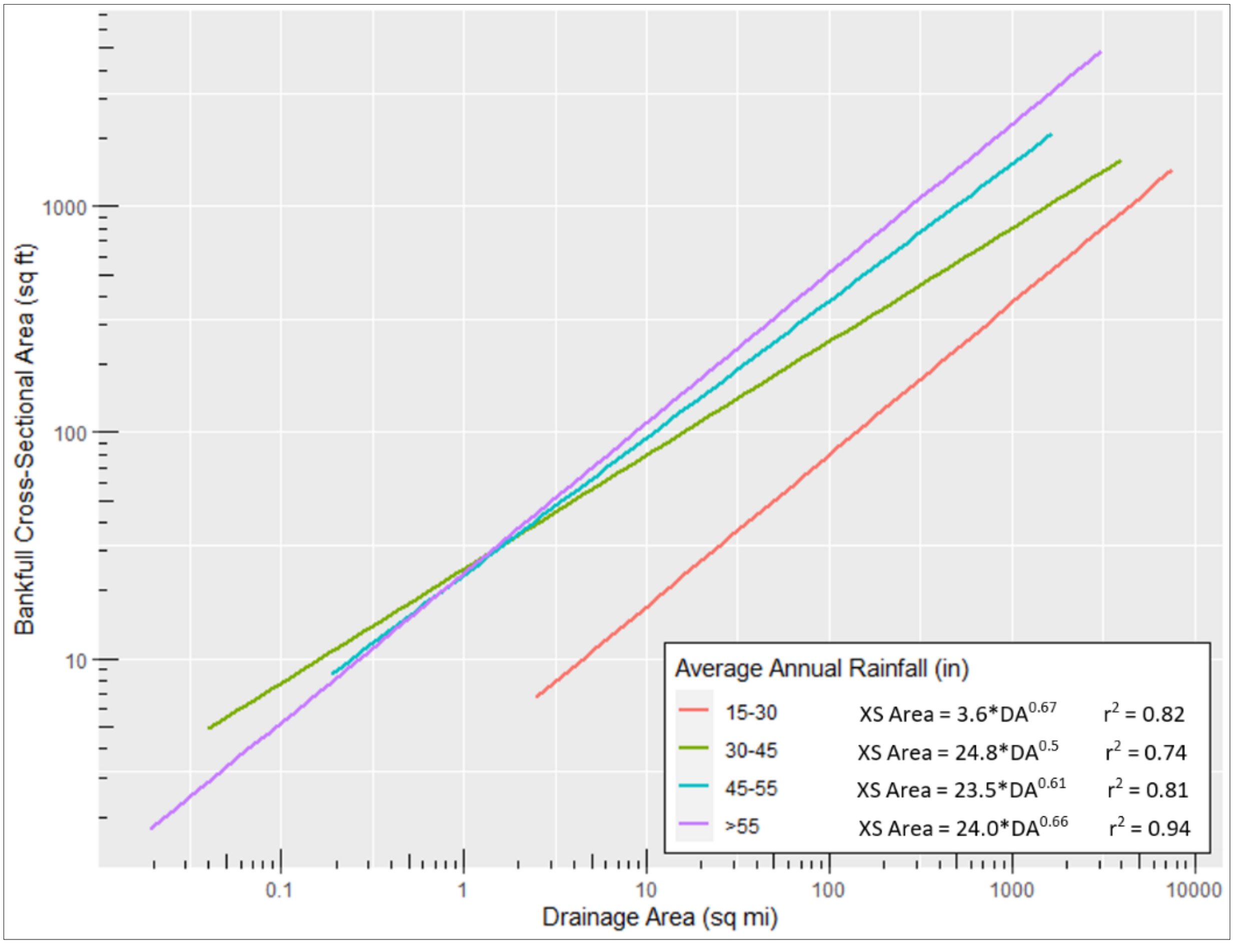


Figure 9. Final rainfall-based regional curves

Accuracy of the rainfall-based regional curves, as provided by the r-squared values, are within the range of r-squared values of existing regional curves, but they are below the median value shown in Figure 10. There is no intention of replacing existing regional curves with this research, however, rainfall-based regional curves can be used to supplement existing data by filling geographical gaps in coverage area of existing regional curves. The results of this research provide a valuable tool used to quickly estimate bankfull cross-sectional area of stream channel anywhere in the country using only two input parameters: average annual rainfall and drainage area. For most of the country, the USGS StreamStats online application can be used to delineate a basin for any point along a stream while also returning basi n statistics such as average annal rainfall. A typical workflow would be to delineate the stream watershed using StreamStats, select the appropriate regional curve based on average annual rainfall, then use the corresponding regression equation with the input variable of drainage area to solve for expected bankfull cross-sectional area.

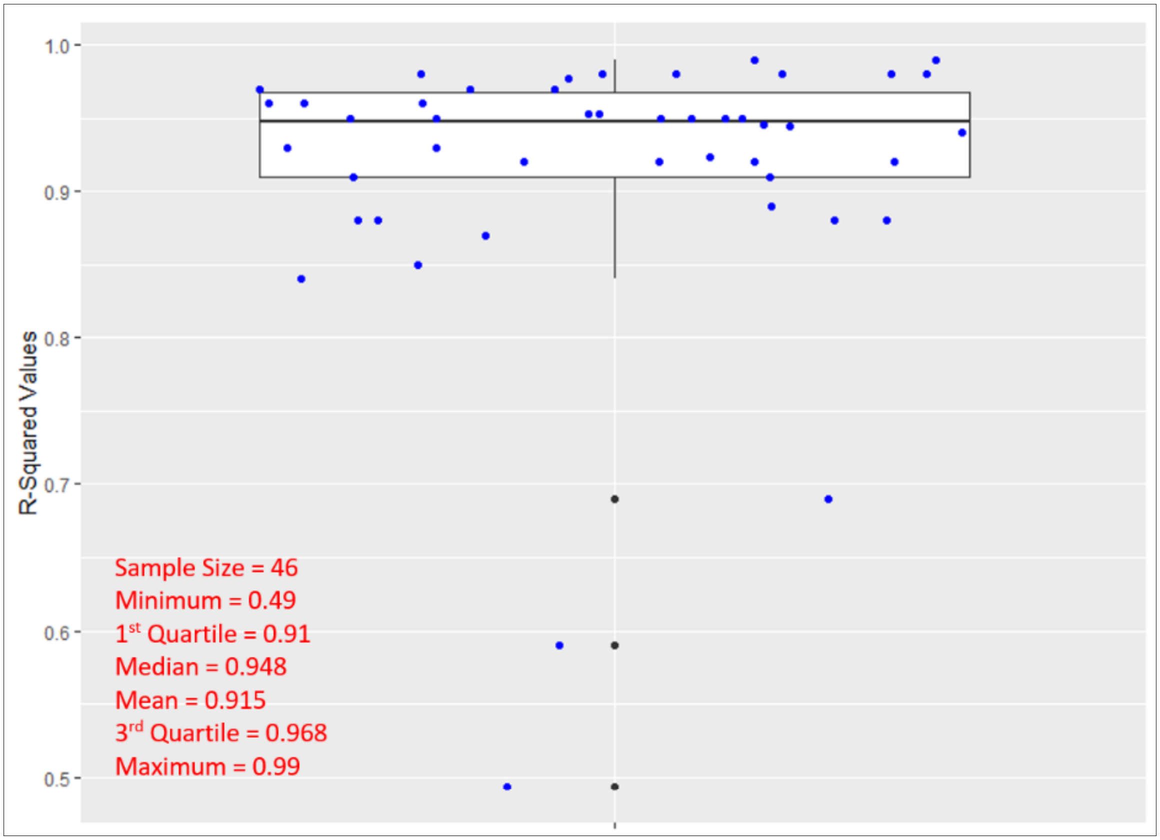


Figure 10. Existing regional curve r-squared distribution

Supplemental Mapping and Digital Data

The final goal of this project was to provide GIS data of the existing regional curves as well as individual drainage basins associated with the 741 basins used in this analysis. The shapefile of the existing regional curves was made my merging the individual basin shapes included in each regional curve. The result is a geographically accurate shape of the combined watershed area. Note that many regional curve shapes comprise multiple disconnected polygons because their individual watershed boundaries are often not directly adjacent to one another. Only 11 regional curve shapes contain individual drainage basins for all data points included in the regional curve study. Missing drainage basins are attributed to either a lack of coordinates provided in the published regional curve report, or because the drainage basins were not included in the existing USGS drainage basin datasets in conjunction with StreamStats not being developed for that area. For regional curves where no drainage basins were available, an approximate shape was manually created in the general vicinity of the study area. A summary of the number of drainage basins used for each regional curve shape is presented in Table 4.

A map of the existing regional curve shapes is provided in Appendix C and GIS data in shapefile format is included in Appendix D. The shapefile also includes the Equation Summary Table (Appendix A) joined to each shape. GIS shapefiles of the existing regional curves can be opened in any GIS software including Google Earth Pro. This shapefile provides practitioners with a valuable tool to quickly locate and reference the closest regional curves to their study site.

Table 4. Data summary for regional curve shapefile

Curve ID	Sample Size	Available Basins	Final Shape	Curve ID	Sample Size	Available Basins	Final Shape
AL_1	21	0	Approximate	NC_1	14	10	Partial
AL_2	43	43	Complete	NC_2	13	10	Partial
AL_3	8	5	Partial	NC_3	16	7	Partial
AR_1	17	17	Complete	NC_4a	17	0	Approximate
AZ_1	58	0	Approximate	NC_4b	13	0	Approximate
CO_1	18	0	Approximate	NC_5	24	8	Partial
CO_2a	13	7	Partial	NM_1	82	0	Approximate
CO_2b	8	4	Partial	NY_1	56	15	Partial
CO_2c	5	4	Partial	NY_2	39	12	Partial
FL_1	14	12	Partial	NY_3	21	10	Partial
FL_2	12	4	Partial	NY_4	9	4	Partial
FL_3a	12	0	Approximate	NY_5	73	16	Partial
FL_3b	14	0	Approximate	NY_6	50	14	Partial
ID_1	75	73	Partial	NY_7	33	10	Partial
ID_2	39	37	Partial	OH_1a	45	45	Complete
IN_1a	25	25	Complete	OH_1b	5	5	Complete
IN_1b	31	31	Complete	PA_1	6	6	Complete
IN_1c	26	26	Complete	PA_2	14	0	Approximate
MA_1	27	27	Complete	PA_3a	11	10	Partial
MD_1	23	20	Partial	PA_3b	55	50	Partial
MD_2	14	10	Partial	VA_1	41	30	Partial
MD_3	14	11	Partial	VA_2	17	12	Partial
MD_4	22	2	Partial	WV_1	37	37	Complete
MI_1	40	37	Partial	WY_1	35	35	Complete

CONCLUSION

For this study, 48 regional curves were investigated. Of the 48 regional curves, 46 were developed as single-variate regression analyses. The 46 single-variate regional curves were used to develop equations applying the Watershed Response Factor methodology. The resulting WRF equation is similar to an equation developed by David Bidelspach which adds validity to the approach.

Given that the Watershed Response Factor methodology assumes that the slope of all regional curves can be represented by a single, mean slope value, it was of interest to approach the WRF concept from a new direction in which the slope of the regression line is also variable. As a result, Rainfall-Based Regional Curves were developed. Four Rainfall-based regional curves were created by classifying the data into four categories based on average annual rainfall. The four curves then utilize traditional regional curve methodology where drainage area is plotted along the x-axis and bankfull cross-sectional area is plotted along the y-axis. Therefore, each curve exhibits variable slope and y-intercept values.

Both methods (Watershed Response Factor and Rainfall-Based Regional Curves) provide a new tool that can be used by practitioners to estimate bankfull cross-sectional area for locations not covered under existing regional curve studies. Resulting values of bankfull cross-sectional area estimated by these two methods are expected to be of similar accuracy as published regional curves. Therefore, these two methods should be used to supplement existing regional curve studies and the development of new regional curves should cease to continue.

Furthermore, additional research should be conducted to apply this methodology to a larger dataset or to investigate other response variables in addition to average annual rainfall. One promising avenue would be to develop a nation, average annual runoff dataset and develop Runoff-Based Regional Curves which were demonstrated on a smaller scale in the study by Metcalf et. al. (2009). To aid in this effort, GIS data created for this study will be shared freely. Lastly, a GIS shapefile has been created which provides a geographically accurate representation of each published regional curve that can be used by practitioners to quickly locate and reference summary data from each regional curve study.

REFERENCES

Ackers, P., and F. G. Charlton. 1970. “Meander geometry arising from varying flows.” *J. Hydrol.*, 11 (3): 230–252. https://doi.org/10.1016/0022-1694(70)90064-8.

Andrews, E. D. 1980. “Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming.” *J. Hydrol.*, 46 (3–4): 311–330. https://doi.org/10.1016/0022-1694(80)90084-0.

Benson, M. A., and D. M. Thomas. 1966. “A DEFINITION OF DOMINANT DISCHARGE.” *Int. Assoc. Sci. Hydrol. Bull.*, 11 (2): 76–80. https://doi.org/10.1080/02626666609493460.

Bent, G. C., and A. M. Waite. 2013. *Equations for Estimating Bankfull Channel Geometry and Discharge for Streams in Massachusetts*. Scientific Investigations Report. Scientific Investigations Report 2013-5155. U.S. Geological Survey.

Blench, T. 1951. “Hydraulics of sediment- bearing canals and rivers: Vancouver.” *Evans Ind. Ltd*.

Brantley, E. 2016a. *Bankfull Regional Curves for the Piedmont Region of Alabama*. Auburn University, College of Agriculture.

Brantley, E. 2016b. *Eco-Morphological Mitigation Design and Assessment Tools for the Alabama and Tennessee Appalachian Plateau*. Auburn University, College of Agriculture.

Castro, J. M., and P. L. Jackson. 2001. “Bankfull Discharge Recurrence Intervals and Regional Hydraulic Geometry Relationships: Patterns in the Pacific Northwest, Usa1.” *JAWRA J. Am. Water Resour. Assoc.*, 37 (5): 1249–1262. https://doi.org/10.1111/j.1752-1688.2001.tb03636.x.

Castro, J. M., and C. R. Thorne. 2019. “The stream evolution triangle: Integrating geology, hydrology, and biology.” *River Res. Appl.*, 35 (4): 315–326. https://doi.org/10.1002/rra.3421.

Chaplin, J. J. 2005. *Development of regional curves relating bankfull-channel geometry and discharge to drainage area for streams in Pennsylvania and selected areas of Maryland*. *Dev. Reg. Curves Relat. Bankfull-Channel Geom. Disch. Drain. Area Streams Pa. Sel. Areas Md.*, Scientific Investigations Report. USGS Numbered Series. U.S. Geological Survey.

Cinotto, P. J. 2003. *Development of regional curves of bankfull-channel geometry and discharge for streams in the non-urban, Piedmont Physiographic Province, Pennsylvania and Maryland*. Water-Resources Investigations Report 03-4014. U.S. Geological Survey.

Copeland, R. R., D. S. Biedenharn, and J. C. Fischenich. 2000. *Channel-Forming Discharge*. U.S. Army Corps of Engineers.

Doll, B. A., A. D. Dobbins, J. Spooner, D. R. Clinton, and D. A. Bidelspach. 2003. *Hydraulic Geometry Relationships for Rural North Carolina Coastal Plain Streams*. 11.

Doll, B. A., D. E. Wise-Frederick, C. M. Buckner, S. D. Wilkerson, W. A. Harman, R. E. Smith, and J. Spooner. 2002. “Hydraulic Geometry Relationships for Urban Streams Throughout the Piedmont of North Carolina.” *JAWRA J. Am. Water Resour. Assoc.*, 38 (3): 641–651. https://doi.org/10.1111/j.1752-1688.2002.tb00986.x.

Dunne, T., and L. B. Leopold. 1978. “Water in Environmental Planning.” *San Franc. CA WH Freeman Co.*, 4 (3): 305–306. https://doi.org/10.1002/esp.3290040322.

Elliott, J. G., and K. D. Cartier. 1986. *Hydraulic geometry and streamflow of channels in the Piceance Basin, Rio Blanco and Garfield counties, Colorado*. U.S. Geological Survey.

Emmett, W. W. 1975. *The Channels and Waters of the Upper Salmon River Area, Idaho*. 115. Professional Paper. U.S. Geological Survey.

Emmett, W. W., and M. G. Wolman. 2001. “Effective discharge and gravel-bed rivers.” *Earth Surf. Process. Landf.*, 26 (13): 1369–1380. https://doi.org/10.1002/esp.303.

Falcone, J. 2011. “GAGES-II: Geospatial Attributes of Gages for Evaluating Streamflow.” U.S. Geological Survey.

Fenneman, N. M., and D. W. Johnson. 1946. “Physical Divisions of the United States.” USGS special map. Washington, D.C.: United States Geological Survey.

FISRWG. 1998. *Stream Corridor Restoration: Principles, Processes, and Practices*. Washington, D.C.? Federal Interagency Stream Restoration Working Group (FISRWG).

Foster, K. 2012. *Bankfull-Channel Geometry and Discharge Curves for the Rocky Mountains Hydrologic Region in Wyoming*. Scientific Investigations Report 2012-5178. U.S. Geological Survey.

Hammer, T. R. 1972. “Stream channel enlargement due to urbanization.” *Water Resour. Res.*, 8 (6): 1530–1540. https://doi.org/10.1029/WR008i006p01530.

Harman, W. A., G. D. Jennings, J. M. Patterson, D. R. Clinton, L. O. Slate, A. G. Jessup, J. R. Everhart, and R. E. Smith. 1999. “Bankfull Hydraulic Geometry Relationships for North Carolina Streams.” *Bankfull Hydraul. Geom. Relatsh. N. C. Streams*, 401–408.

Harman, W. A., D. E. Wise, M. A. Walker, R. Morris, M. A. Cantrell, M. Clemmons, G. D. Jennings, D. Clinton, and J. M. Patterson. 2000. “Bankfull Hydraulic Geometry Relationships for North Carolina Streams.” Accessed April 7, 2020. https://web.archive.org/web/20170705004308/https://www.bae.ncsu.edu/programs/extension/wqg/srp/mtnpaper.html.

Harvey, A. M. 1969. “Channel capacity and the adjustment of streams to hydrologic regime.” *J. Hydrol.*, 8 (1): 82–98. https://doi.org/10.1016/0022-1694(69)90032-8.

Johnson, P. A., and B. J. Fecko. 2008. “Regional channel geometry equations: a statistical comparison for physiographic provinces in the eastern US.” *River Res. Appl.*, 24 (6): 823–834. https://doi.org/10.1002/rra.1080.

Keaton, J. N., T. Messinger, and E. J. Doheny. 2005. *Development and analysis of regional curves for streams in the non-urban valley and ridge physiographic province, Maryland, Virginia, and West Virginia*. *Dev. Anal. Reg. Curves Streams Non-Urban Val. Ridge Physiogr. Prov. Md. Va. W. Va.*, Scientific Investigations Report. USGS Numbered Series.

Krstolic, J. L., and J. J. Chaplin. 2007. *Bankfull Regional Curves for Streams in the Non-Urban, Non-Tidal Coastal Plain Physiographic Province, Virginia and Maryland*. *Bankfull Reg. Curves Streams Non-Urban Non-Tidal Coast. Plain Physiogr. Prov. Va. Md.*, Scientific Investigations Report. USGS Numbered Series. Geological Survey (U.S.).

Leopold, L. B., and T. Maddock. 1953. “of Stream Channels and Some Physiographic Implications.” 64.

Leopold, L. B., and H. E. Skibitzke. 1967. “Observations on Unmeasured Rivers.” *Geogr. Ann. Ser. Phys. Geogr.*, 49 (2/4): 247–255. [Wiley, Swedish Society for Anthropology and Geography]. https://doi.org/10.2307/520892.

Lotspeich, R. R. 2009. *Regional Curves of Bankfull Channel Geometry for Non-Urban Streams in the Piedmont Physiographic Province, Virginia*. *Reg. Curves Bankfull Channel Geom. Non-Urban Streams Piedmont Physiogr. Prov. Va.*, Scientific Investigations Report. USGS Numbered Series. U.S. Geological Survey.

Mackin, J. H. 1948. “Concept of The Graded River.” *Bull. Geol. Soc. Am.*, 59: 463–512.

McCandless, T. L. 2003a. *Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Allegheny Plateau and the Valley and Ridge Hydrologic Regions*. U.S. Fish and Wildlife Service.

McCandless, T. L. 2003b. *Maryland Stream Survey: Bankfull Discharge and Channel Characteristics in the Coastal Plain Hydrologic Region*. U.S. Fish and Wildlife Service.

McCandless, T. L., and R. A. Everett. 2002. *Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Piedmont Hydrologic Region*. 175. U.S. Fish and Wildlife Service.

Messinger, T. 2009. *Regional Curves for Bankfull Channel Characteristics in the Appalachian Plateaus, West Virginia*. *Reg. Curves Bankfull Channel Charact. Appalach. Plateaus W. Va.*, Scientific Investigations Report. USGS Numbered Series. U.S. Geological Survey.

Metcalf, C. 2004. *Regional Channel Characteristics for Maintaining Natural Fluvial Geomorphology in Florida Streams*. U.S. Fish and Wildlife Services.

Metcalf, C. 2005. *Alabama Riparian Reference Reach and Regional Curve Study*. 37. U.S. Fish and Wildlife Services.

Metcalf, C. K., S. D. Wilkerson, and W. A. Harman. 2009. "Bankfull Regional Curves for North and Northwest Florida Streams." *JAWRA J. Am. Water Resour. Assoc.*, 45 (5): 1260–1272. https://doi.org/10.1111/j.1752-1688.2009.00364.x.

Miller, S. J., and D. Davis. 2003. *Identifying and Optimizing Regional Relations for Bankfull Discharge and Hydraulic Geometry at USGS Stream Gage Sites in the Catskill Mountais: NY*. 24. New York City Department of Environmental Protection Technical Report.

Moody, T., M. Wirtanen, and S. N. Yard. 2003. *Regional Relationships for Bankfull Stage in Natural Channels of the Arid Southwest*. 38. Natural Channel Design, Inc.

Mulvihill, C. I., and B. P. Baldigo. 2007. *Regionalized Equations for Bankfull-Discharge and Channel Characteristics of Streams in New York State- Hydrologic Region 3 East of the Hudson River*. Scientific Investigations Report. Scientific Investigations Report 2007-5227. U.S. Geological Survey.

Mulvihill, C. I., A. G. Ernst, and B. P. Baldigo. 2005. *Regionalized Equations for Bankfull Discharge and Channel Characteristics of Streams in New York State: Hydrologic Region 6 in the Southern Tier of New York*. Scientific Investigations Report. Scientific Investigations Report 2005-5100. U.S. Geological Survey.

Mulvihill, C. I., A. Filopowicz, A. Coleman, and B. P. Baldigo. 2007. *Regionalized Equations for Bankfull Discharge and Channel Characteristics of Streams in New York State—Hydrologic Regions 1 and 2 in the Adirondack Region of Northern New York*. Scientific Investigations Report. Scientific Investigations Report 2007-5189. U.S. Geological Survey.

Pickup, G., and R. F. Warner. 1976. "Effects of hydrologic regime on magnitude and frequency of dominant discharge." *J. Hydrol.*, 29 (1–2): 51–75. https://doi.org/10.1016/0022-1694(76)90005-6.

Pugh, A. L., and R. K. Redman. 2019. *Regional Hydraulic Geometry Characteristics of Streams in the Ouachita Mountains of Arkansas*. Scientific Investigations Report 2019-1104. U.S. Geological Survey.

Rachol, C. M., and K. Boley-Morse. 2009. *Estimated Bankfull Discharge for Selected Michigan Rivers and Regional Hydraulic Geometry Curves for Estimating Bankfull Characteristics in Southern Michigan Rivers*. Scientific Investigations Report. Scientific Investigations Report 2009-5133. U.S. Geological Survey.

Radecki-Pawlik, A. 2002. "Bankfull discharge in mountain streams: theory and practice." *Earth Surf. Process. Landf.*, 27 (2): 115–123. https://doi.org/10.1002/esp.259.

Riley, S. J. 1972. "A comparison of morphometric measures of bankfull." *J. Hydrol.*, 17 (1–2): 23–31. https://doi.org/10.1016/0022-1694(72)90064-9.

Robinson, B. A. 2013. *Regional Bankfull-Channel Dimensions of Non-Urban Wadeable Streams in Indiana*. Scientific Investigations Report. USGS Numbered Series. U.S. Geological Survey.

Schumm, S. A. 1960. "The shape of alluvial channels in relation to sediment type." *Prof. Pap.* https://doi.org/10.3133/pp352B.

Sherwood, J. M., and C. A. Huitger. 2005. *Bankfull characteristics of Ohio streams and their relation to peak streamflows*. *Bankfull Charact. Ohio Streams Their Relat. Peak Streamflows*, Scientific Investigations Report. USGS Numbered Series.

Sweet, W. V., and J. W. Geratz. 2003. "Bankfull Hydraulic Geometry Relationships and Recurrence Intervals for North Carolina's Coastal Plain." *JAWRA J. Am. Water Resour. Assoc.*, 39 (4): 861–871. https://doi.org/10.1111/j.1752-1688.2003.tb04411.x.

USGS. 2012. “USGS Streamgage NHDPlus Version 1 Basins 2011.” U.S. Geological Survey.
USGS. 2016. *StreamStats: Streamflow Statistics and Spatial Analysis Tools for Water-Resources Applications*. U.S. Geological Survey.
USGS. 2021. “USA_Mean_Rainfall.” *ArcGIS Online*. Accessed January 23, 2022. https://www.arcgis.com/home/item.html?id=f9bca1b8229b425c8972547099e0c671.
Westergard, B. E., C. I. Mulvihill, A. G. Ernst, and B. P. Baldigo. 2004. *Regionalized Equations for Bankfull-Discharge and Channel Characteristics of Streams in New York State: Hydrologic Region 5 in Central New York*. Scientific Investigations Report. Scientific Investigations Report 2004-5247. U.S. Geological Survey.
White, K. E. 2001. *Regional curve development and selection of a reference reach in the non-urban, lowland sections of the Piedmont physiographic province, Pennsylvania and Maryland*. Water-Resources Investigations Report 01-4146. U.S. Geological Survey.
Williams, G. P. 1978. “Bank-Full Discharge of Rivers.” *Water Resour. Res.*, 14 (6): 1141–1154. https://doi.org/10.1029/WR014i006p01141.
Wolman, M. G. 1955. *The natural channel of Brandywine Creek, Pennsylvania*. *Nat. Channel Brand. Creek Pa.*, Professional Paper. USGS Numbered Series. U.S. Government Printing Office.
Wolman, M. G., and L. B. Leopold. 1957. *River flood plains: Some observations on their formation*. *River Flood Plains Some Obs. Their Form.*, Professional Paper, 87109. USGS Numbered Series. Washington, D.C.: U.S. Government Printing Office.
Wolman, M. G., and J. P. Miller. 1960. “Magnitude and Frequency of Forces in Geomorphic Processes.” *J. Geol.*, 68 (1): 54–74. https://doi.org/10.1086/626637.
Woodyer, K. D. 1968. “Bankfull frequency in rivers.” *J. Hydrol.*, 6 (2): 114–142. https://doi.org/10.1016/0022-1694(68)90155-8.
Yochum, S. E. 2003. *Regional Characteristics for the Lower Willow Creek Stream Restoration*. U.S. Department of Agriculture Natural Resources Conservation Service.

APPENDICES

Appendix A – Summary Tables

Appendix B – Rainfall Curve Comparisons

Appendix C – Supplemental Data Mapping

Appendix D – GIS Data (Digital Only)

Appendix A
Summary Tables

Standard Attribute Table

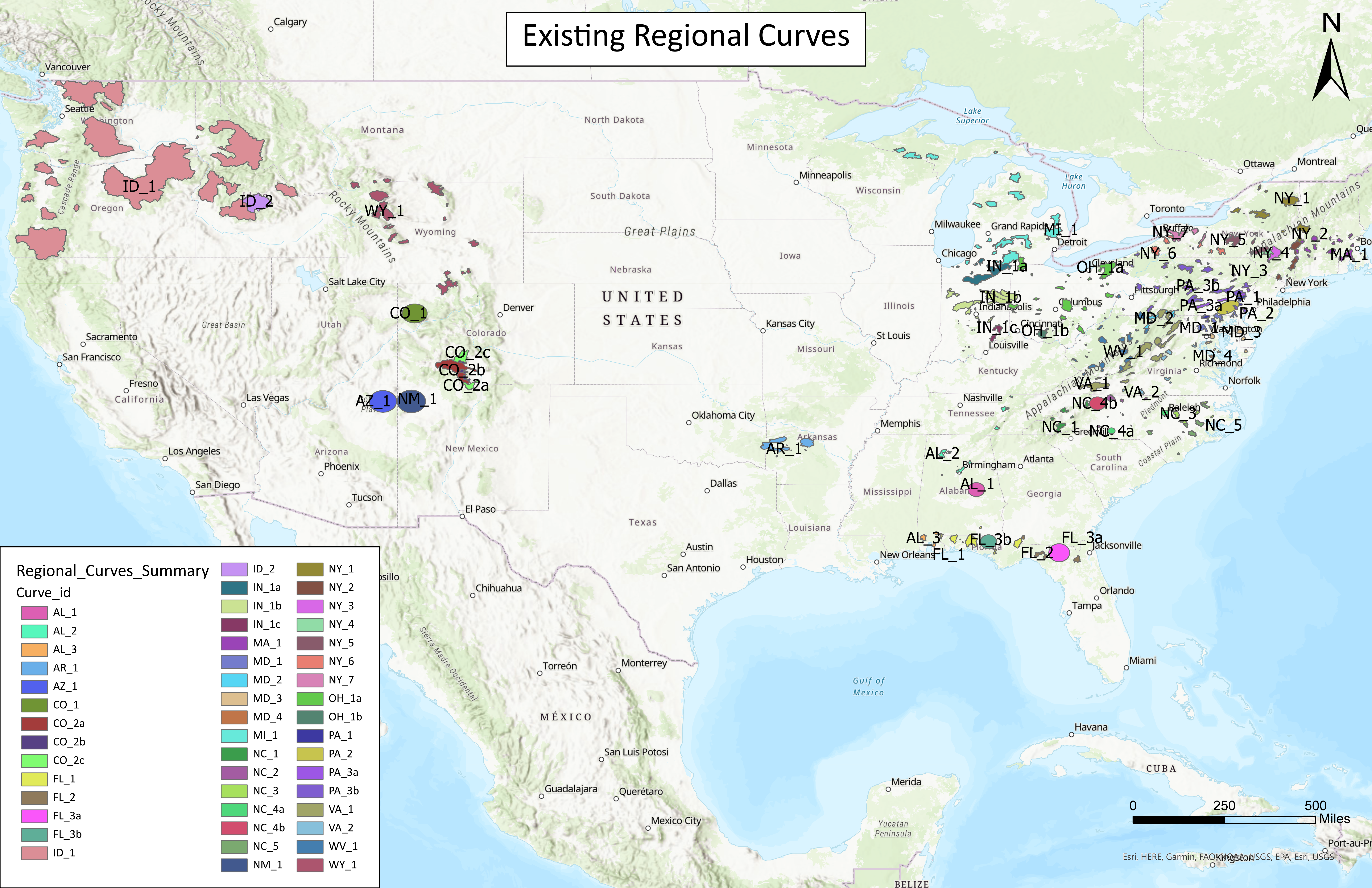
Curve ID	Reference	Notes	Latitude	Longitude	USGS Gage Number	Ungaged Number	Site Name	Site Number	Drainage Area (mi^2)	Bankfull Cross-Sectional Area (ft^2)	Bankfull Width (ft)	Bankfull Mean Depth (ft)	Bankfull Max Depth (ft)	Bankfull Velocity (ft/s)	Bankfull Discharge (ft^3/s)	Return Period (years)	Channel Slope (ft/ft)	Sinuosity	Width/Mean Depth Ratio	Flood Prone Width (ft)	Entrenchment Ratio	Rosgen Classification	Grain Size d_{10} (mm)	Grain Size d_{50} (mm)	Grain Size d_{84} (mm)
AR_1	(Pugh and Redman 2019)		34.473056	-93.960556	07355900		Big Fork Tributary at Big Fork, Ark.		0.19	6.82	10.3	0.66					0.019	1.05	15.6	18	1.7	B4		7.1	
AR_1	(Pugh and Redman 2019)		34.620833	-94.204167	07355800		Lewis Creek Tributary near Mena, Ark.		0.65	31.2	31.7	0.98					0.033	1.05	32.3	124	3.9	C4		22.0	
AR_1	(Pugh and Redman 2019)		34.496667	-94.668333	07338780		Mountain Fork Tributary near Smithville, Okla.		0.68	22.2	22.9	0.97					0.011	1.18	23.6	82	3.6	B4c		25.5	
AR_1	(Pugh and Redman 2019)		34.565833	-93.617500	07356700		Barnes Branch near Mount Ida, Ark.		1.85	51.3	29.6	1.73					0.007	1.10	17.1	74	2.5	C4		33.9	
AR_1	(Pugh and Redman 2019)		34.361111	-93.458333	07359750		Little Sugarloaf Creek near Bonnerdale, Ark.		2.32	33.8	21.4	1.58					0.011	1.25	13.5	39	1.8	B4c		3.8	
AR_1	(Pugh and Redman 2019)		34.366944	-92.866944	07359520		Jackson Creek near Malvern, Ark.		2.95	50.4	37.5	1.68					0.002	1.14	22.3	87	2.3	C4		4.1	
AR_1	(Pugh and Redman 2019)		34.626056	-93.052667	07357700		Glazypeau Creek at Mountain Valley, Ark.		3.84	69.6	37.3	1.86					0.005	1.38	20.1	287	7.7	C4		4.1	
AR_1	(Pugh and Redman 2019)		34.112890	-94.040471	07341100		Rock Creek near Dierks, Ark.		9.46	188.9	70.8	2.67					0.008	1.49	26.5	510	7.2	C4		20.5	
AR_1	(Pugh and Redman 2019)		34.514444	-94.337222	07338700		Twomile Creek near Hatfield, Ark.		15.9	331.9	112.6	2.95					0.006	1.20	38.2	373	3.3	C4		27.3	
AR_1	(Pugh and Redman 2019)		34.797500	-92.933889	07362587		Alum Fork Saline River near Reform, Ark.		27	436.9	123	3.68					0.007	1.07	33.5	321	2.6	C4		20.5	
AR_1	(Pugh and Redman 2019)		34.638333	-94.612500	07335700		Kiamichi River near Big Cedar, Okla.		36.9	559.5	138.5	4.04					0.004	1.22	34.3	542	2.9	C3		6.3	
AR_1	(Pugh and Redman 2019)		34.311667	-93.899722	07360200		Little Missouri River near Langley, Ark.		68.4	752.3	161.1	4.67					0.002	1.26	34.5	303.04	1.9	B4c		39.2	
AR_1	(Pugh and Redman 2019)		34.380000	-94.236389	07340300		Cossatot River near Vandervoort, Ark.		89.6	1691	270.9	6.24					0.003	1.48	43.4	377	1.4	B4c		5.3	
AR_1	(Pugh and Redman 2019)		34.382778	-93.606111	07359610		Caddo River near Caddo Gap, Ark.		136	1290	219.1	5.89					0.002	1.48	37.2	385	1.8	B4c		20.9	
AR_1	(Pugh and Redman 2019)		34.462222	-94.635000	07338750		Mountain Fork at Smithville, Okla.		322	2127	216.6	9.82					0.000	2.50	22.1	397	1.8	B3c		89.3	
AR_1	(Pugh and Redman 2019)		34.872500	-93.657222	07261500		Fourche LaFave River near Gravelly, Ark.		410	2945	339.8	9.42					0.001	1.50	36.1	1,820	5.4	C4c		47.3	
AR_1	(Pugh and Redman 2019)		34.567778	-92.610278	07363000		Saline River at Benton, Ark.		550	1691	270.9	6.24					0.002	1.23	43.4	3,767	13.9	C4		21.4	

Regional Curve Summary Table																					
			Drainage Area (sq mi)		Cross-Sectional Area (sq ft)				Width (ft)				Depth (ft)				Discharge (cfs)				
Number	Curve ID	Reference	Min	Max	Eqn	y-int	exp.	r^2	Eqn	y-int	exp.	r^2	Eqn	y-int	exp.	r^2	Eqn	y-int	exp.	r^2	
1	AL_1	(Brantley 2016b)	0.08	94	$A_{bkf} = 24.46*DA^{0.65}$	24.46	0.65	0.96	$W_{bkf} = 17.88*DA^{0.34}$	17.88	0.34	0.94	$D_{bkf} = 1.32*DA^{0.32}$	1.32	0.32	0.87	$Q_{bkf} = 84.21*DA^{0.78}$	84.21	0.78	0.92	
2	AL_2	(Brantley 2016a)	0.02	101	$A_{bkf} = 26.5*DA^{0.71}$	26.50	0.71	0.98	$W_{bkf} = 17.87*DA^{0.38}$	17.87	0.38	0.97	$D_{bkf} = 1.46*DA^{0.34}$	1.46	0.34	0.94	$Q_{bkf} = 94.72*DA^{0.75}$	94.72	0.75	0.91	
3	AL_3	(Metcalf 2005)	3.40	125	$A_{bkf} = 4.35*DA^{0.99}$	4.35	0.99	0.98	$W_{bkf} = 5.67*DA^{0.52}$	5.67	0.52	0.94	$D_{bkf} = 0.78*DA^{0.47}$	0.78	0.47	0.96	$Q_{bkf} = 10.94*DA^{0.94}$	10.94	0.94	0.93	
4	AR_1	(Pugh and Redman 2019)	0.19	550	$A_{bkf} = 29.85*DA^{0.757}$	29.85	0.76	0.97	$W_{bkf} = 25.3*DA^{0.43}$	25.30	0.43	0.94	$D_{bkf} = 1.2*DA^{0.328}$	1.20	0.33	0.97	$Q_{bkf} = 111*DA^{0.872}$	111.00	0.87	0.98	
5	AZ_1	(Moody et al. 2003)	0.80	5009	$A_{bkf} = 11.96*DA^{0.54}$	11.96	0.54	0.93	$W_{bkf} = 15.76*DA^{0.32}$	15.76	0.32	0.82	$D_{bkf} = .78*DA^{0.22}$	0.78	0.22	0.73	$Q_{bkf} = 88.73*DA^{0.47}$	88.73	0.47	0.66	
6	CO_1	(Elliott and Cartier 1986)	3.58	630	$A_{bkf} = 0.5*DA^{0.72}$	0.50	0.72	0.69													
7	CO_2a	(Yochum 2003)	2.70	104	$A_{bkf} = 11.4*DA^{0.21}$	11.40	0.21	0.84	$W_{bkf} = 8.71*DA^{0.20}$	8.71	0.20	0.84									
8	CO_2b	(Yochum 2003)	21.60	1691																	
9	CO_2c	(Yochum 2003)	17.60	518																	
10	FL_1	(Metcalf 2004)	1.00	198	$A_{bkf} = 17.1*DA^{0.64}$	17.10	0.64	0.99	$W_{bkf} = 10.4*DA^{0.39}$	10.40	0.39	0.96	$D_{bkf} = 1.64*DA^{0.25}$	1.64	0.25	0.86	$Q_{bkf} = 27.7*DA^{0.71}$	27.70	0.71	0.95	
11	FL_2	(Metcalf 2004)	1.50	474	$A_{bkf} =6.1*DA^{0.71}$	6.10	0.71	0.98	$W_{bkf} = 9.2*DA^{0.28}$	9.20	0.28	0.85	$D_{bkf} = 0.67*DA^{0.43}$	0.67	0.43	0.84	$Q_{bkf} = 7.54*DA^{0.77}$	7.54	0.77	0.92	
12	FL_3a	(Metcalf et al. 2009)	0.90	198	$A_{bkf} =6.1*DA^{0.71}$	6.10	0.71	0.98	$W_{bkf} = 9.2*DA^{0.28}$	9.20	0.28	0.85	$D_{bkf} = 0.67*DA^{0.43}$	0.67	0.43	0.84	$Q_{bkf} = 7.54*DA^{0.77}$	7.54	0.77	0.92	
13	FL_3b	(Metcalf et al. 2009)	1.50	474	$A_{bkf} = 17.1*DA^{0.64}$	17.10	0.64	0.99	$W_{bkf} = 10.4*DA^{0.96}$	10.40	0.39	0.96	$D_{bkf} = 1.64*DA^{0.25}$	1.64	0.25	0.86	$Q_{bkf} = 27.7*DA^{0.71}$	27.70	0.71	0.95	
14	ID_1	(Castro and Jackson 2001)	17.70	8080	$A_{bkf} = 10.86*DA^{0.643}$	10.86	0.64	0.49	$W_{bkf} = 11.8*DA^{0.38}$	11.80	0.38	0.49	$D_{bkf} =1.13 *DA^{0.24}$	1.13	0.24	0.29	$Q_{bkf} = 50.93*DA^{0.67}$	50.93	0.67	0.44	
15	ID_2	(Emmett 1975)	2.50	1800	$A_{bkf} = 5.6*DA^{0.65}$	5.60	0.65	0.92	$W_{bkf} = 8.1*DA^{0.38}$	8.10	0.38	0.84	$D_{bkf} = .69*DA^{0.27}$	0.69	0.27	0.88	$Q_{bkf} = 28.3*DA^{0.69}$	28.30	0.69	0.96	
16	IN_1a	(Robinson 2013)	0.14	941	$A_{bkf} = 17*DA^{0.495}$	17.00	0.50	0.92	$W_{bkf} = 13.4*DA^{0.318}$	13.40	0.32	0.92	$D_{bkf} = 1.3*DA^{0.176}$	1.30	0.18	0.75					
17	IN_1b	(Robinson 2013)	0.40	812	$A_{bkf} = 28.8*DA^{0.487}$	28.80	0.49	0.88	$W_{bkf} = 18.2*DA^{0.327}$	18.20	0.33	0.94	$D_{bkf} = 1.6*DA^{0.159}$	1.60	0.16	0.56					
18	IN_1c	(Robinson 2013)	0.06	186	$A_{bkf} = 50.9*DA^{0.468}$	50.90	0.47	0.87	$W_{bkf} = 27.2*DA^{0.286}$	27.20	0.29	0.94	$D_{bkf} = 1.9*DA^{0.183}$	1.90	0.18	0.58					
19	MA_1	(Bent and Waite 2013)	2.55	183	$A_{bkf} = 14.1*DA^{0.703}$	14.10	0.70	0.91	$W_{bkf} = 15*DA^{0.404}$	15.00	0.40	0.88	$D_{bkf} = .95*DA^{0.82}$	0.95	0.30	0.82	$Q_{bkf} = 37.1*DA^{0.8}$	37.10	0.80	0.77	
20	MD_1	(McCandless and Everett 2002)	1.47	102	$A_{bkf} = 17.42*DA^{0.73}$	17.42	0.73	0.95	$W_{bkf} = 14.78*DA^{0.39}$	14.78	0.39	0.83	$D_{bkf} = 1.18*DA^{0.34}$	1.18	0.34	0.86	$Q_{bkf} = 84.56*DA^{0.76}$	84.56	0.76	0.93	
21	MD_2	(McCandless 2003a)	0.20	102	$A_{bkf} = 13.17*DA^{0.75}$	13.17	0.75	0.93	$W_{bkf} = 13.87*DA^{0.44}$	13.87	0.44	0.92	$D_{bkf} = .95*DA^{0.31}$	0.95	0.31	0.91	$Q_{bkf} = 34.02*DA^{0..94}$	34.02	0.94	0.99	
22	MD_3	(McCandless 2003b)	0.30	113	$A_{bkf} = 10.34*DA^{0.7}$	10.34	0.70	0.96	$W_{bkf} = 10.3*DA^{0.38}$	10.30	0.38	0.80	$D_{bkf} = 1.01*DA^{0.32}$	1.01	0.32	0.87					
23	MD_4	(Krstolic and Chaplin 2007)	0.28	113	$A_{bkf} = 11.9899*DA^{0.63803}$	11.99	0.64	0.95	$W_{bkf} = 10.4459*DA^{0.36543}$	10.45	0.37	0.89	$D_{bkf} = 1.145*DA^{0.27345}$	1.15	0.27	0.87	$Q_{bkf} = 28.3076*DA^{0.59834}$	28.31	0.60	0.79	
24	MI_1	(Rachol and Boley-Morse 2009)	16.30	401	$A_{bkf} = 4.38*DA^{0.74}$	4.38	0.74	0.59	$W_{bkf} = 8.19*DA^{0.44}$	8.19	0.44	0.69	$D_{bkf} = 0.67*DA^{0.27}$	0.67	0.27	0.28	$Q_{bkf} = 4.05*DA^{0.95}$	4.05	0.95	0.60	
25	NC_1	Harman et al. 2000	2.00	126	$A_{bkf} = 22.1*DA^{0.67}$	22.10	0.67	0.88	$W_{bkf} = 19.9*DA^{0.36}$	19.90	0.36	0.81	$D_{bkf} = 1.1*DA^{0.31}$	1.10	0.31	0.79	$Q_{bkf} = 115.7*DA^{0.73}$	115.70	0.73	0.88	
26	NC_2	(Harman et al. 1999)	0.20	128	$A_{bkf} = 21.43*DA^{0.68}$	21.43	0.68	0.95	$W_{bkf} = 11.89*DA^{0.43}$	11.89	0.43	0.81	$D_{bkf} = 1.5*DA^{0.32}$	1.50	0.32	0.88	$Q_{bkf} = 66.57*DA^{0.89}$	66.57	0.89	0.97	
27	NC_3	(Doll et al. 2003)	0.22	161	$A_{bkf} = 14.52*DA^{0.66}$	14.52	0.66	0.88	$W_{bkf} = 10.97*DA^{0.36}$	10.97	0.36	0.87	$D_{bkf} = 1.29*DA^{0.3}$	1.29	0.30	0.74	$Q_{bkf} = 16.56*DA^{0.72}$	16.56	0.72	0.90	
28	NC_4a	(Doll et al. 2002)	0.20	42.6	$A_{bkf} = 58.6*DA^{0.65}$	58.60	0.65	0.95	$W_{bkf} = 24.6*DA^{0.33}$	24.60	0.33	0.88	$D_{bkf} = 2.4*DA^{0.33}$	2.40	0.33	0.87	$Q_{bkf} = 295.7*DA^{0.63}$	295.70	0.63	0.94	
29	NC_4b	(Doll et al. 2002)	0.20	128	$A_{bkf} = 21.4*DA^{0.67}$	21.40	0.67	0.95	$W_{bkf} = 13.7*DA^{0.36}$	13.70	0.36	0.91	$D_{bkf} = 1.6*DA^{0.29}$	1.60	0.29	0.86	$Q_{bkf} = 89*DA^{0.71}$	89.00	0.71	0.87	
30	NC_5	(Sweet and Geratz 2003)	0.60	182	$A_{bkf} = 9.43*DA^{0.74}$	9.43	0.74	0.96	$W_{bkf} = 9.64*DA^{0.38}$	9.64	0.38	0.95	$D_{bkf} = .98*DA^{0.36}$	0.98	0.36	0.92	$Q_{bkf} = 8.79*DA^{0.76}$	8.79	0.76	0.92	
31	NM_1	(Moody et al. 2003)	0.30	9730	$A_{bkf} = 4.78*DA^{0.51}$	4.78	0.51	0.92	$W_{bkf} = 9.91*DA^{0.28}$	9.91	0.28	0.80	$D_{bkf} = 0.47*DA^{0..24}$	0.47	0.24	0.72	$Q_{bkf} = 15.31*DA^{0.61}$	15.31	0.61	0.86	
32	NY_1	(Mulvihill et al. 2007)	0.52	396	$A_{bkf} = 22.3*DA^{0.694}$	22.30	0.69	0.97	$W_{bkf} = 21.5*DA^{0.362}$	21.50	0.36	0.89	$D_{bkf} = 1.06*DA^{0.329}$	1.06	0.33	0.89	$Q_{bkf} = 49.6*DA^{0.849}$	49.60	0.85	0.95	
33	NY_2	(Mulvihill and Baldigo 2007)	0.42	329	$A_{bkf} = 39.8*DA^{0.5}$	39.80	0.50	0.92	$W_{bkf} = 24*DA^{0.292}$	24.00	0.29	0.85	$D_{bkf} = 1.66*DA^{0.21}$	1.66	0.21	0.77	$Q_{bkf} = 83.8*DA^{0.67}$	83.80	0.67	0.93	
34	NY_3	(Miller and Davis 2003)	3.72	237	$A_{bkf} = 17.9*DA^{0.777}$	17.90	0.78	0.91	$W_{bkf} = 17.1*DA^{0.46}$	17.10	0.46	0.87	$D_{bkf} = 1.07*DA^{0.314}$	1.07	0.31	0.84	$Q_{bkf} = 117.2*DA^{0.78}$	117.20	0.78	0.81	
35	NY_4	(Miller and Davis 2003)	11.40	163	$A_{bkf} = 7.2*DA^{0.894}$	7.20	0.89	0.97	$W_{bkf} = 9.1*DA^{0.545}$	9.10	0.55	0.98	$D_{bkf} = 0.79*DA^{0.35}$	0.79	0.35	0.88	$Q_{bkf} = 30.3*DA^{0.98}$	30.30	0.98	0.99	
36	NY_5	(Westergard et al. 2004)	0.70	332	$A_{bkf} = 10.8*DA^{0.823}$	10.80	0.82	0.98	$W_{bkf} = 13.5*DA^{0.449}$	13.50	0.45	0.92	$D_{bkf} = 0.82*DA^{0.373}$	0.82	0.37	0.92	$Q_{bkf} = 45.3*DA^{0.856}$	45.30	0.86	0.96	
37	NY_6	(Mulvihill et al. 2005)	1.02	290	$A_{bkf} = 17.6*DA^{0.662}$	17.60	0.66	0.89	$W_{bkf} = 16.9*DA^{0.419}$	16.90	0.42	0.79	$D_{bkf} = 1.04*DA^{0.244}$	1.04	0.24	0.64	$Q_{bkf} = 48*DA^{0.842}$	48.00	0.84	0.90	
38	NY_7	(Mulvihill et al. 2006)	1.07	349	$A_{bkf} = 15.9*DA^{0.656}$	15.90	0.66	0.95	$W_{bkf} = 10.8*DA^{0.458}$	10.80	0.46	0.89	$D_{bkf} = 1.47*DA^{0.199}$	1.47	0.20	0.52	$Q_{bkf} = 37.1*DA^{0.765}$	37.10	0.77	0.94	
39	OH_1a	(Sherwood and Huitger 2005)	0.29	685	$A_{bkf} = 27.1*DA^{0.621}$	27.10	0.62	0.95	$W_{bkf} = 18*DA^{0.356}$	18.00	0.36	0.91	$D_{bkf} = 1.52*DA^{0.265}$	1.52	0.27	0.88	$Q_{bkf} = 93.3*DA^{0.637}$	93.30	0.64	0.82	
40	OH_1b	(Sherwood and Huitger 2005)	0.55	387	$A_{bkf} = 64.5*DA^{0.621}$	64.50	0.62	0.95	$W_{bkf} = 32*DA^{0.356}$	32.00	0.36	0.91	$D_{bkf} = 2.02*DA^{0.265}$	2.02	0.27	0.88	$Q_{bkf} = 230*DA^{0.637}$	230.00	0.64	0.82	
41	PA_1	(White 2001)	2.57	102	$A_{bkf} = 11.69*DA^{0.8517}$	11.69	0.85	0.98	$W_{bkf} = 14.8*DA^{0.4613}$	14.80	0.46	0.79	$D_{bkf} = .7804*DA^{0.3919}$	0.78	0.39	0.84	$Q_{bkf} = 69.60*DA^{0.793}$	69.60	0.79	0.98	
42	PA_2	(Cinotto 2003)	2.57	102	$A_{bkf} = 12.4*DA^{0.81}$	12.40	0.81	0.94	$W_{bkf} = 13.6*DA^{0.469}$	13.60	0.47	0.80	$D_{bkf} = 0.912*DA^{0.339}$	0.91	0.34	0.72	$Q_{bkf} = 53.1*DA^{0.842}$	53.10	0.84	0.93	
43	PA_3a	(Chaplin 2005)	2.57	216	$A_{bkf} = 8.62*DA^{0.734}$	8.62	0.73	0.88	$W_{bkf} = 9.83*DA^{0.449}$	9.83	0.45	0.81	$D_{bkf} = .894*DA^{0.284}$	0.89	0.28	0.76	$Q_{bkf} = 44.29*DA^{0.634}$	44.29	0.63	0.73	
44	PA_3b	(Chaplin 2005)	3.45	214	$A_{bkf} = 12.04*DA^{0.797}$	12.04	0.80	0.92	$W_{bkf} = 14.65*DA^{0.449}$	14.65	0.45	0.81	$D_{bkf} = .875*DA^{0.33}$	0.88	0.33	0.72	$Q_{bkf} = 43.21*DA^{0.867}$	43.21	0.87	0.92	
45	VA_1	(Keaton et al. 2005)	0.10	247	$A_{bkf} = 12.595*DA^{0.7221}$	12.60	0.72	0.94	$W_{bkf} = 12.445*DA^{0.4362}$	12.45	0.44	0.89	$D_{bkf} = 1.001*DA^{0.2881}$	1.00	0.29	0.87	$Q_{bkf} = 43.249*DA^{0.7938}$	43.25	0.79	0.91	
46	VA_2	(Lotspeich 2009)	0.29	111	$A_{bkf} = 11.636*DA^{0.7981}$	11.64	0.80	0.95	$W_{bkf} = 12.964*DA^{0.4294}$	12.96	0.43	0.91	$D_{bkf} = .892*DA^{0.3721}$	0.89	0.37	0.92	$Q_{bkf} = 43.895*DA^{0.9472}$	43.90	0.95	0.95	
47	WV_1	(Messinger 2009)	0.80	205	$A_{bkf} = 20.4865*DA^{0.7133}$	20.49	0.71	0.98	$W_{bkf} = 20.989*DA^{0.3725}$	20.99	0.37	0.95	$D_{bkf} = 1.067*DA^{0.3128}$	1.07	0.31	0.88	$Q_{bkf} = 59.81*DA^{0.8538}$	59.81	0.85	0.96	
48	WY_1	(Foster 2012)	1.50	699	$A_{bkf} = 8.57*DA^{0.62}$	8.57	0.62	0.85	$W_{bkf} = 8.22*DA^{0.44}$	8.22	0.44	0.80	$D_{bkf} = 1.04*DA^{0.18}$	1.04	0.18	0.48	$Q_{bkf} = 24.55*DA^{0.73}$	24.55	0.73	0.77	

Appendix B
Rainfall Curve Comparisons

Trial Number	Precipitation Ranges - Avg. Annual Rainfall (in)	Sample Size	Regression Slope	Regression Intercept	Regression Equation	r-squared
	All data	741	0.54	23.07	XS Area = 23.07*DA^0.54	0.74
1	15-25	28	0.66	3.15	XS Area = 3.15*DA^0.66	0.8
	25-35	98	0.58	8.78	XS Area = 8.78*DA^0.58	0.74
	35-45	298	0.53	25.43	XS Area = 25.43*DA^0.53	0.8
	45-55	191	0.61	23.45	XS Area = 23.45*DA^0.61	0.81
	>55	126	0.66	23.96	XS Area = 23.96*DA^0.66	0.94
2	15-20	5	0.64	2.68	XS Area = 2.68*DA^0.64	0.94
	20-25	23	0.69	2.96	XS Area = 2.96*DA^0.69	0.76
	25-30	33	0.64	5.15	XS Area = 5.15*DA^0.64	0.83
	30-35	65	0.59	9.63	XS Area = 9.63*DA^0.59	0.72
	35-40	127	0.5	22.53	XS Area = 22.53*DA^0.5	0.79
	40-45	171	0.57	26.96	XS Area = 26.96*DA^0.57	0.85
	45-50	149	0.6	23.38	XS Area = 23.38*DA^0.6	0.8
	50-55	42	0.62	24.2	XS Area = 24.2*DA^0.62	0.85
	55-60	72	0.66	24.59	XS Area = 24.59*DA^0.66	0.96
	60-65	23	0.67	25.14	XS Area = 25.14*DA^0.67	0.89
	65-70	11	0.72	13.61	XS Area = 13.61*DA^0.72	0.9
	>70	20	0.67	23.54	XS Area = 23.54*DA^0.67	0.71
3	15-25	28	0.66	3.15	XS Area = 3.15*DA^0.66	0.8
	25-30	33	0.64	5.15	XS Area = 5.15*DA^0.64	0.83
	30-35	65	0.59	9.63	XS Area = 9.63*DA^0.59	0.72
	35-40	127	0.5	22.53	XS Area = 22.53*DA^0.5	0.79
	40-45	171	0.57	26.96	XS Area = 26.96*DA^0.57	0.85
	45-50	149	0.6	23.38	XS Area = 23.38*DA^0.6	0.8
	50-55	42	0.62	24.2	XS Area = 24.2*DA^0.62	0.85
	55-60	72	0.66	24.59	XS Area = 24.59*DA^0.66	0.96
	60-65	23	0.67	25.14	XS Area = 25.14*DA^0.67	0.89
	65-70	11	0.72	13.61	XS Area = 13.61*DA^0.72	0.9
	>70	20	0.67	23.54	XS Area = 23.54*DA^0.67	0.71
4	15-25	28	0.66	3.15	XS Area = 3.15*DA^0.66	0.8
	25-35	98	0.58	8.78	XS Area = 8.78*DA^0.58	0.74
	35-45	298	0.53	25.43	XS Area = 25.43*DA^0.53	0.8
	45-55	191	0.61	23.45	XS Area = 23.45*DA^0.61	0.81
	55-65	95	0.66	24.7	XS Area = 24.7*DA^0.66	0.95
	>65	31	0.75	14.19	XS Area = 14.19*DA^0.75	0.86
5	15-30	61	0.67	3.64	XS Area = 3.64*DA^0.67	0.82
	30-45	363	0.5	24.82	XS Area = 24.82*DA^0.5	0.74
	45-60	263	0.62	23.03	XS Area = 23.03*DA^0.62	0.9
	>60	54	0.68	21.6	XS Area = 21.6*DA^0.68	0.88
6	15-25	28	0.66	3.15	XS Area = 3.15*DA^0.66	0.8
	25-50	545	0.5	25.55	XS Area = 25.55*DA^0.5	0.71
	>50	168	0.65	23.59	XS Area = 23.59*DA^0.65	0.94
7	15-30	61	0.67	3.64	XS Area = 3.64*DA^0.67	0.82
	30-50	512	0.52	25.11	XS Area = 25.11*DA^0.52	0.74
	>50	168	0.65	23.59	XS Area = 23.59*DA^0.65	0.94
8	15-30	61	0.67	3.64	XS Area = 3.64*DA^0.67	0.82
	30-45	363	0.5	24.82	XS Area = 24.82*DA^0.5	0.74
	45-55	191	0.61	23.45	XS Area = 23.45*DA^0.61	0.81
	>55	126	0.66	23.96	XS Area = 23.96*DA^0.66	0.94

Appendix C
Supplemental Data Mapping


Existing Regional Curves
N
Regional_Curves_Summary
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AL_2
AL_3
AR_1
AZ_1
CO_1
CO_2a
CO_2b
CO_2c
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FL_2
FL_3a
FL_3b
ID_1
ID_2
IN_1a
IN_1b
IN_1c
MA_1
MD_1
MD_2
MD_3
MD_4
MI_1
NC_1
NC_2
NC_3
NC_4a
NC_4b
NC_5
NM_1
NY_1
NY_2
NY_3
NY_4
NY_5
NY_6
NY_7
OH_1a
OH_1b
PA_1
PA_2
PA_3a
PA_3b
VA_1
VA_2
WV_1
WY_1
0
250
500
Miles
Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, Esri, USGS

Appendix D
GIS Data (Digital Only)