Prepared in cooperation with the U.S. Army Corps of Engineers

Regional Regression Equations for Estimation of Four Hydraulic Properties of Streams at Approximate Bankfull Conditions for Different Ecoregions in Texas

Scientific Investigations Report 2020–5086

U.S. Department of the Interior
U.S. Geological Survey

Cover. Examples of generally shallow, sand-bedded streams at U.S. Geological Survey (USGS) streamgages in the western part of the Rolling Plains ecoregion. Photographs by the U.S. Geological Survey.

Front. USGS streamgage 07307800 Pease River near Childress, Texas on March 22, 2006, looking upstream from the gage toward the west.

Back. USGS streamgage 07308500 Red River near Burkburnett, Texas on August 18, 2011, looking downstream from the gage toward the southeast.

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2020

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Suggested citation:
Asquith, W.H., Gordon, J.D., and Wallace, D.S., 2020, Regional regression equations for estimation of four hydraulic properties of streams at approximate bankfull conditions for different ecoregions in Texas: U.S. Geological Survey Scientific Investigations Report 2020–5086, 45 p., https://doi.org/10.3133/sir20205086.

ISSN 2328-0328 (online)

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Velocity	
foot per second (ft/s)	0.3048	meter per second (m/s)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations

AIC	Akaike Information Criterion
NSE	Nash-Sutcliffe efficiency
NWIS	National Water Information System
RSE	residual standard error
USGS	U.S. Geological Survey
VARsd	standard deviation of response variable

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Abstract

The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, assessed statistical relations between hydraulic properties of streams at approximate bankfull conditions for different ecological regions (ecoregions) in Texas. Data from more than 103,000 records of measured discharge and ancillary hydraulic properties were assembled from summaries of discharge measurements for 424 U.S. Geological Survey streamgages in Texas. The data were subsequently subsetted at each streamgage for a streamgage-specific discharge interval centered on the estimated median annual peak discharge (0.5 annual exceedance probability) obtained from previously published regional regression equations in Texas in conjunction with the streamgage-specific sample median annual peak discharge for the period of record for each streamgage. Discharge measurements at gaged locations representing bankfull conditions (approximated from a discharge interval centered on the estimated median annual peak discharge at a given site) and associated watershed properties were subjected to rigorous statistical analysis. For most discharge measurements (where discharge is symbolically represented as Q), the following hydraulic properties are available: cross-section area (A), water-surface top width (B), and reported mean velocity (V). Statewide summary statistics were computed by using these four hydraulic properties (Q, A, B, and V) and the following five watershed properties: (1) watershed area (contributing drainage area), (2) a multiple of main-channel slope (1,000 times main-channel slope), (3) mean annual precipitation, (4) drainage density, and (5) sinuosity ratio. From the initial set of 424 streamgages, summary statistics were computed for 372 selected streamgages in Texas and constitute the subsetted measurements dataset described in this report. Eight of the 10 ecoregions in Texas are represented in the statewide summary statistics.

The resulting statistical relations, expressed as regression equations, can be used to estimate cross-section area, water-surface top width, discharge, and mean velocity of streams in different Texas ecoregions, at approximate bankfull conditions. In the regression equations, watershed properties were the independent variables for applicable watersheds, and predictions from the equations might be useful for estimating the four hydraulic properties at ungaged or unmonitored locations from selected characteristics measured at both the ungaged locations and gaged locations.

Four regression equations to estimate the four hydraulic properties were identified as the preferred equations from this study. The four preferred equations use watershed area, mean annual precipitation, and aggregated ecoregion (treated as a categorical variable) to estimate the hydraulic properties, and justification is provided for this preference. For the four equations, the proportions of variance explained by the regression equations as measured by Nash-Sutcliffe efficiency are about 71 percent for cross-section area, 36 percent for top width, 76 percent for discharge, and 25 percent for mean velocity. Residual standard error (RSEs) of the regression equations are 0.252 log10 square feet for cross-section area, 0.319 log10 feet for top width, 0.247 log10 cubic feet per second for discharge, and 0.190 log10 feet per second for mean velocity, and the corresponding standard deviations of response are 0.465 log10 square feet, 0.397 log10 feet, 0.507 log10 cubic feet per second, and 0.220 log10 feet per second, respectively. The residual standard errors are less than the standard deviations as anticipated but show that the uncertainty reduction (percent change) for cross-section area is about −46 percent, about −20 percent for top width, about −51 percent for discharge, and about −14 percent for mean velocity.

Introduction

Quantification of the hydraulic properties of streams at bankfull conditions has numerous applications in hydrologic studies and engineering design. Johnson and Heil (1996, p. 1283) explain that “bankfull elevation and discharge are used in a number of ways by engineers, ecologists, and geomorphologists in studying stream behavior and in planning and designing stream restoration designs.” Conceptually, the term “bankfull discharge” refers to the amount of flow that fills the channel without overtopping the banks (Wu and others, 2008), and is often considered equivalent to the term "channel-forming discharge" in stable stream systems where the stream is neither aggrading nor degrading (Biedenharn and others, 2000, Biedenharn and others, 2001; Messinger, 2009; Mulvihill and others, 2009).

To help quantify hydraulic properties at bankfull conditions of streams for different ecological regions of Texas (ecoregions), the U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers, investigated statistical relations between hydraulic properties of selected measurements of discharge (streamflow) and various watershed properties for different ecoregions in Texas (fig. 1). Bankfull conditions were approximated by discharge measurements of a magnitude considered approximate to median annual peak discharge; selected measurements have a discharge that is within a range centered on estimates of median annual peak discharge from both regional regression equations and observational data.

Four hydraulic properties of streams were assessed for this report (cross-sectional area, water-surface top width, discharge, and mean velocity) by using linear regression methods. The regression equations resulting from this type of statistical assessment are at times referred to in the literature as "regional curves" (Dutnell, 2000; Lotspeich, 2009; Messinger, 2009). The regression equations represent ensembles of bankfull discharge and associated hydraulic properties as a function of watershed area for different ecoregions in Texas.

Purpose and Scope

This report documents the development of regional regression equations for estimation of four hydraulic properties of streams—cross-section area (*A*), water-surface top width (*B*), discharge (*Q*), and mean velocity (*V*)—in different ecoregions in Texas at approximate bankfull conditions. Individual discharge measurements made at USGS streamgages provided the *A*, *B*, *Q*, and *V* values used in the regression analyses; *A*, *B*, and *V* values were associated with specific *Q* values that were within a streamgage-specific discharge interval centered on an estimated median annual peak discharge in order to approximate bankfull conditions at an individual stream. Watershed properties of contributing drainage area, main-channel slope, mean annual precipitation, and ecoregion were used as predictor variables for the regression analyses. Regional regression equations were ultimately developed for 8 of the 10 ecoregions in Texas where sufficient streamgaging data were available for analysis; statewide regional regression equations also were developed. An additional 12 statewide regression equations are presented for combinations of predictor variables but explicitly lack ecoregion. Statewide summary statistics complementing the regression equations were computed from the four hydraulic properties (*Q*, *A*, *B*, and *V*) and selected watershed properties. The summary statistics and regression equations described in this report are published in a companion software release (Asquith and Wallace, 2020).

Background and Previous Studies

USGS discharge measurements provide a wealth of information that can be used to assess the hydraulic properties of streams. For more than 125 years, USGS personnel in Texas have made direct measurements of discharge and observations of zero flow (that is, dry channel conditions) as part of the operational support of a statewide streamgage network (Slade and others, 2001; Lurry, 2011). When first queried for this assessment on April 28, 2015, the USGS National Water Information System (NWIS) contained about 194,000 discharge measurements made in Texas (U.S. Geological Survey, 2015a). This total includes thousands of zero-flow values recorded for numerous stream locations, particularly in west Texas where the climate is arid to semiarid (Larkin and Bomar, 1983).

USGS discharge measurements provide summaries of extensive field-collected data regardless of the techniques used to make the measurements, which have changed over time (Turnipseed and Sauer, 2010). In addition to the volume of flow per unit of time, individual discharge measurements generally contain field-collected supporting information (hydraulic properties), such as cross section area and water-surface top width, detailed information about the channel cross section, and discharge velocity in typically 10 to 25 subsections of the channel that compose the cross section. Until about 2006, most discharge measurements were made by means of current-meter-based techniques inclusive of mechanical and acoustic velocity-meter use. After about 2006, hydroacoustic techniques for measuring discharge have been predominately used (Turnipseed and Sauer, 2010; U.S. Geological Survey, 2015b; Kevin Oberg, U.S. Geological Survey, written commun., 2016).

The National Research Council (1999, p. 29) states that a "wealth of information on geomorphology could be extracted from the USGS's vast discharge measurement file." The National Research Council (2004, p. 122–123) goes on to state, "surprisingly, the USGS and other groups have not published hydraulic geometry relations * * * for hydroclimatic regions of the United States. A consequence of this is that [situations requiring] hydraulic geometry try [to] use either 'average' hydraulic geometry relations, which are often the data from Leopold and Maddock (1953) or stream classification schemes * * *."

Data from more than 103,000 records of measured discharge and ancillary hydraulic properties were assembled from summaries of discharge measurements for 424 U.S. Geological Survey streamgages in Texas. This study demonstrates that the great number of records, wide range of flow conditions, and large number of streamgages contained within the USGS discharge measurement database in Texas facilitates the regionalization of discharge as well as mean velocity and other hydraulic properties (see section titled "Computation of Summary Statistics From Hydraulic and Watershed Properties"). Locations of 424 USGS streamgages in Texas initially considered for this investigation are shown in figure 1; the associated ecoregions and watershed properties for the 424 streamgages are published in the companion software release (Asquith and Wallace, 2020).

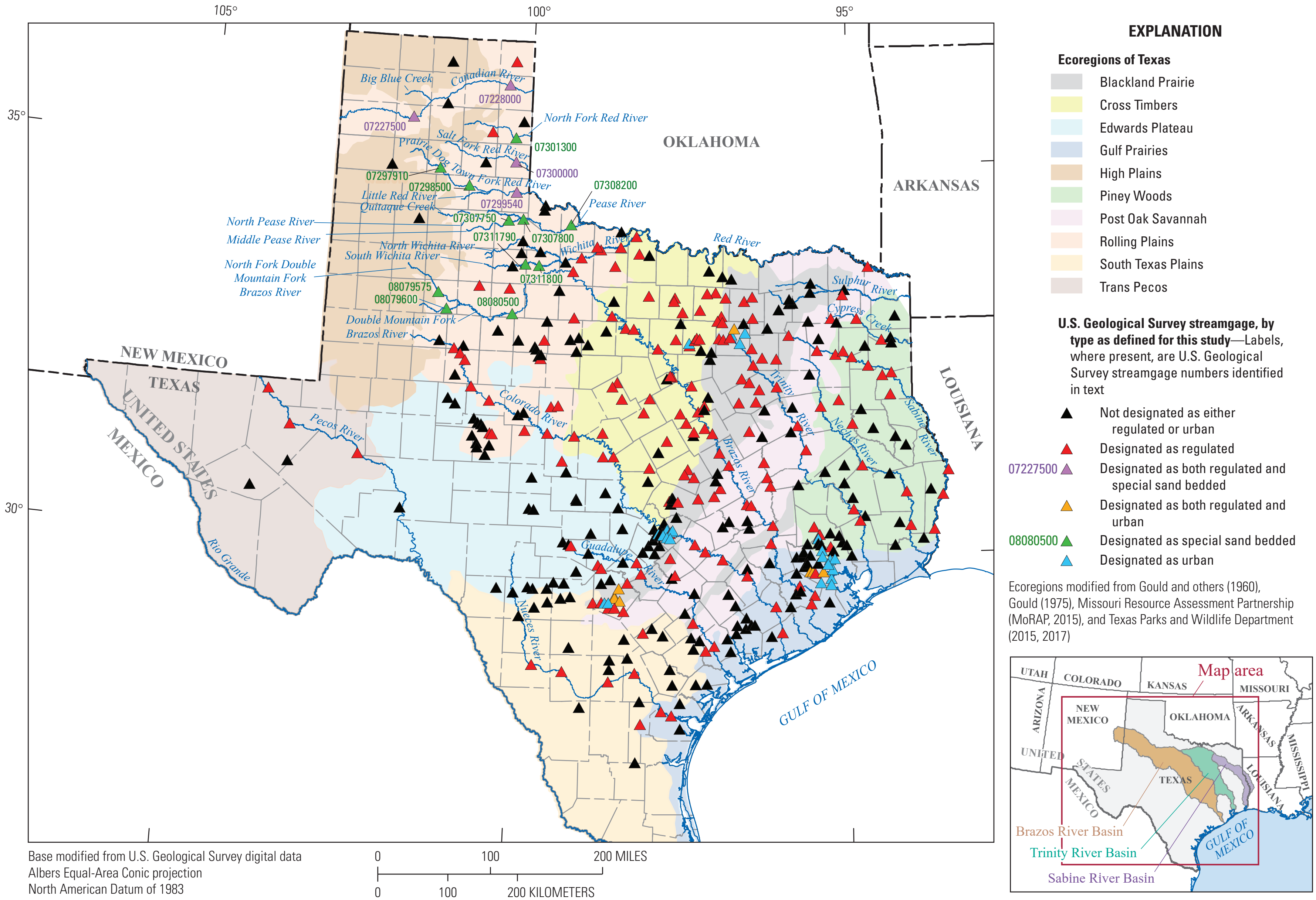

Figure 1. Ecoregions and locations of 424 U.S. Geological Survey streamgages considered for this study of four hydraulic properties for Texas.

Regionalization refers to a framework for statistical analyses that produces procedures for estimation of various properties, such as discharge, at ungaged or unmonitored locations from selected characteristics measured at both the ungaged locations and gaged locations. The statistical relations, expressed as regression equations, can be used to estimate basic hydraulic properties of channels from watershed properties (independent variables) for applicable watersheds and might be useful for engineering design purposes. Regional regression equations to predict hydraulic properties from discharge-related data and watershed properties are reported herein that are similar to those in earlier Texas-based studies (Asquith and others, 2013; Cleveland and others, 2013; Asquith, 2014); these regional studies demonstrate that indeed a wealth of hydraulic information can be associated with simple metrics of channel morphology and stream location, as anticipated by the National Research Council (1999).

Regional Studies of Discharge Statistics in Texas

Many studies of statistical regionalization of discharge statistics in Texas have been made such as those by Slade and others (1995), Asquith and others (1996), Asquith and Slade (1997), Raines and Asquith (1997), Asquith (1998), Lanning-Rush (2000), Rifai and others (2000), Asquith (2001), Asquith and Thompson (2008), and Asquith and Roussel (2009). Often the primary interest in these types of statistical regionalization studies is to transfer hydrologic quantities of interest such as discharge information from gaged to ungaged locations. These studies generally involve a presentation of one or more equations for estimation of a discharge statistic, such as the median annual peak discharge or the peak discharge having a 0.5 annual exceedance probability, commonly referred to as the “2-year return period peak discharge” or more simply as the “2-year peak discharge.”

Other studies have provided historical perspectives of various discharge trends and discharge characteristics in Texas (Asquith and Heitmuller, 2008; Villarini and Smith, 2013; Asquith and Barbie, 2014). A simple-to-use regionalization technique is the drainage-area-ratio method that is used to transfer discharge between locations on the basis of the ratio of respective watershed areas (Asquith and others, 2006). Asquith (2010) discusses further historical context of hydrologic regionalization of discharge data in Texas.

Regional Studies of Discharge Measurements in Texas

Some relatively recent regional studies of discharge measurements in Texas have been completed that are complementary to this report. A study by Cleveland and others (2013) describes selected USGS discharge measurement data in Texas and the relation of various hydraulic and hydrologic topics of interest to drainage design of transportation infrastructure. Cleveland and others (2013, p. 88–96) provide an example computation of bankfull discharge inferred from a flow-duration curve. Flow-duration curves are described by Archfield and others (2007, 2010) and Vogel and Fennessey (1994, 1995). Cleveland and others (2013, fig. 44) demonstrate a relation between discharge and water-surface top width for a Texas stream by using data collected at a streamgage. Finally, Cleveland and others (2013) also provide several graphs depicting relations between a dimensionless bankfull discharge to dimensionless variables (or expressions) such as top width, hydraulic depth, and main-channel slope, as well as three open-channel hydraulic parameters of Froude number, Chezy resistance coefficient, and Shield number. Sturm (2010) provides definitions of Froude number, Chezy resistance coefficient, and Shield number.

Asquith and others (2013) provide a regression procedure to estimate discharge on the basis of generalized additive regression modeling procedures as well as another regression procedure to estimate mean velocity. Generalized additive regression modeling is thoroughly described by Hastie and Tibshirani (1990) and Wood (2006; 2015). The study by Asquith and others (2013) was the first statewide, large-scale, regional statistical study of the USGS discharge measurement database in Texas. For the Asquith and others (2013) study, a database containing more than 17,700 discharge records and ancillary hydraulic properties was assembled from discharge measurement summaries for more than 400 streamgages in Texas. For each discharge measurement, the reported discharge exceeded the 90th percentile for daily mean discharge, as determined by period-of-record, streamgage-specific, flow-duration curves. Each discharge measurement incorporated by Asquith and others (2013) was assumed with some quantification to represent direct-runoff conditions.

Generalized additive modeling was used by Asquith and others (2013) as the regression technique and produced readily implemented procedures to estimate discharge and mean velocity from predictor variables at ungaged stream locations (fig. 2). The resulting discharge model uses predictor variables of cross-section area, top width, stream location, 30-year mean annual precipitation, and a dimensionless OmegaEM parameter, which is a generalized terrain and climate index developed by Asquith and Roussel (2009). Throughout this report, the specific period of 1981–2010 was used for the 30-year mean annual precipitation (hereinafter referred to as the “mean annual precipitation”). Following protocols of Asquith and Roussel (2009, p. 3) and Asquith and others (2013, p. 1337), given the many sources of uncertainty, authors of these previous publications consider that any authoritative source of mean annual precipitation for a suitably long period (perhaps 30 years) is sufficient for substitution into the regression equations described in the current (2020) report. The mean-velocity model uses predictor variables of discharge, top width, stream location, mean annual precipitation, and OmegaEM. The Asquith and others (2013) study concludes with example applications and computations using both the discharge and mean-velocity models (fig. 2).

Asquith and others (2013) Discharge Model—The generalized additive model for estimation of discharge from hydraulic properties and other explanatory variables in the authors' unit system is

$$\log_{10}(Q) = -0.2896 + 1.269\log_{10}(A) - 0.2247\log_{10}(B) + 0.2865\Omega + f_5(\text{longitude}, \text{latitude}) + f_6(P),$$

where $\log_{10}$ is base-10 logarithm; Q is discharge, in cubic meters per second; A is cross-section area, in square meters; B is top width, in meters; Ω is the dimensionless OmegaEM parameter from Asquith and Roussel (2009); P is mean annual precipitation, in millimeters; and f_5 and f_6 are "smooth functions" of the indicated predictor variables (Asquith and others, 2013, figs. 5 and 6). The adjusted coefficient of determination (adjusted R-squared) (Helsel and Hirsch, 2002; Faraway, 2005) is about 0.95, and the residual standard error (RSE) is about 0.22 base-10 logarithm of cubic meters per second. For this analysis, the mean annual precipitation during 1981–2010 was used. Any authoritative source of mean annual precipitation for a suitably long period (perhaps 30 years) is sufficient.

Asquith and others (2013) Mean-Velocity Model—The generalized additive model for estimation of mean velocity ($\overline{V}$) from hydraulic properties and other explanatory variables in the authors' unit system is

$$\overline{V}^{1/5} = 0.9758 + 0.1588\log_{10}(Q) - 0.1820\log_{10}(B) + 0.0854\Omega + f_9(\text{longitude}, \text{latitude}) + f_{10}(P),$$

where f_9 and f_{10} are "smooth functions" of the indicated predictor variables (Asquith and others, 2013, figs. 9 and 10). The adjusted R-squared is about 0.67, and the RSE is about 0.063 one-fifth root of the velocity, in meters per second.

Figure 2. Principal results of Asquith and others (2013) from regionalization of U.S. Geological Survey discharge measurements in Texas of discharge and mean velocity associated with direct-runoff conditions (modified from Asquith and others, 2013, p. 59) and in the original (metric) unit system of that report.

Asquith (2014) is complementary to Asquith and others (2013), with a focus on a different subset of discharge measurements in Texas than those used by Asquith and others (2013). For the Asquith (2014) study, a dataset containing more than 16,300 discharge records and ancillary hydraulic attributes was assembled from summaries of discharge measurement records for more than 380 streamgages in Texas. Each discharge is between the 40th- and 60th-percentile daily mean discharge as determined by period-of-record, streamgage-specific, flow-duration curves. Each discharge measurement incorporated by Asquith (2014) was assumed with some quantification to be near the median discharge conditions, as computed from daily mean discharge values (emphasis on the daily mean, meaning not median annual peak discharge and not the median annual discharge). Such flow conditions are conceptualized as representative of relatively midrange to base-flow conditions in much of the state.

In Asquith (2014), conventional ordinary least squares regression (Helsel and Hirsch, 2002; Faraway, 2005) was used to develop equations to estimate discharge and mean velocity from predictor variables at ungaged stream locations (fig. 3). The discharge regression equation uses cross-section area, top width, contributing drainage area of the watershed (watershed area), and mean annual precipitation of the location. The mean-velocity regression equation uses discharge, top width, watershed area, and mean annual precipitation. The relation between watershed area and main-channel slope (a measure of whole-watershed slope) was depicted by Asquith (2014, fig. 2, p. 111) to aid judgment of equation applicability for ungaged sites. The Asquith (2014) study contains example applications and computations for the discharge and mean-velocity regression equations reproduced in figure 3. The two studies by Asquith and others (2013) and Asquith (2014) are thus highly relevant to this current (2020) assessment, and a similar

Asquith (2014) Discharge Equation—The ordinary-least squares regression equation for estimation of discharge from hydraulic properties and other explanatory variables in the author's unit system is

$$\log_{10}(Q) = -2.323 + 0.9647\log_{10}(A) + 0.1406\log_{10}(B) + 0.1226\log_{10}(W) + 0.4332\log_{10}(P) - 0.03460\log_{10}(A)\times\log_{10}(B),$$

where $\log_{10}$ is base-10 logarithm; Q is discharge, in cubic meters per second; A is cross-section area, in square meters; B is water-surface top width, in meters; W is contributing drainage area, in square kilometers; and P is mean annual precipitation, in millimeters. The adjusted coefficient of determination (adjusted R-squared) (Helsel and Hirsch, 2002; Faraway, 2005) is about 0.95, and the residual standard error (RSE) is about 0.23 base-10 logarithm of cubic meters per second. For this analysis, the mean annual precipitation during 1981–2010 was used. Any authoritative source of mean annual precipitation for a suitably long period (perhaps 30 years) is sufficient.

Asquith (2014) Mean-Velocity Equation—The ordinary-least squares regression equation for estimation of mean velocity ($\overline{V}$) from hydraulic properties and other explanatory variables in the author's unit system is

$$\overline{V}^{1/3} = 1.702 + 0.2119\log_{10}(Q) - 0.2694\log_{10}(B) - 0.01591\log_{10}(W) - 0.2349\log_{10}(P),$$

for which the adjusted R-squared is about 0.50, and the RSE is about 0.087 one-third-root meters per second.

Figure 3. Principal results of Asquith (2014) from regionalization of U.S. Geological Survey discharge measurements in Texas of discharge and mean velocity associated with median discharge conditions from daily mean discharge values (not median annual peak discharge), modified from Asquith (2014) and in original (metric) unit system of that report.

discharge-measurement subsetting process was used in this assessment and in these previous assessments. The subsetting process is described in detail in the "Discharge Measurements Considered Approximate to Bankfull Conditions (the Subsetted Measurements)" section of this report.
Companion to Asquith and others (2013) and Asquith (2014), a report by Asquith and Burley (2013, p. 129) discusses the influence of selected definitions of slope on statistical analyses of discharge measurements, including main-channel slope and proximal slope:

> Watersheds and stream channels can be quantified by various physical properties. A commonly used property in statistical analysis of streamflow and streamflow hydraulics is slope. The "main-channel slope," which is a slope characteristic of a watershed, is a frequently used definition of slope for statistical analysis. The slope of a stream channel near a U.S. Geological Survey (USGS) streamgage or "proximal slope" also is a physically and intuitively important component in analysis of streamflow hydraulics. There is anticipation that proximal slope should be more statistically related to streamflow hydraulic properties such as mean velocity and discharge than main-channel slope based on principles of open-channel hydraulics (Sturm, 2010). The anticipation in part exists because the morphology of a stream channel is partly formed by local topography, and because through hydraulic feedback mechanisms, channel slope responds to bed and bank sediment properties * * *. Simplified mathematics of open-channel hydraulics with local friction slope also indicate that proximal slope should be more relevant than main-channel slope, which is intended to be representative of the watershed and not necessarily specific or arbitrary stream channel locations.

The study by Asquith and Burley (2013) concludes that neither main-channel slope nor proximal slope proved useful as explanatory variables of discharge in Texas. The lack of usefulness of main-channel slope and proximal slope as explanatory variables of discharge is attributable in part to watershed area and slopes often being closely related variables and that the inclusion of watershed area alone is often sufficient to represent slope (main-channel or proximal) as an explanatory variable.

Additional Studies of Basic Hydraulic Properties

Additional studies throughout the United States describe relations between basic hydraulic properties and one or more explanatory variables and cofactors (non-continuous variables). Explanatory variables include watershed properties, channel substrate, geologic and physiographic setting, and ecological and climate regimes. These investigations range from case studies conducted at single locations to broad comprehensive studies done at regional scales. Often, the study locations are coincident with streamgages, and the stage-discharge rating curves (U.S. Geological Survey, 2015d) for the streamgages were utilized. Comparatively few studies have used USGS discharge measurements directly, but many instead rely on field-based surveying of stream channels at applicable study locations and USGS stage-discharge rating curves, which contrasts the statistically based methods of this assessment.

The breadth of the literature pertaining to stream hydraulic properties is far too expansive to succinctly review, so only selected studies are mentioned. A major foundational component, however, of most hydraulic-property studies is the generalization of these properties based on site-surveying of a few to hundreds of representative stream reaches in a given study area. For example, Castro and Jackson (2001) investigated statistical relations between various hydraulic elements for 76 streamgages in the Pacific Northwest of the United States. A conceptual precursor for discharge estimation from channel properties is provided by Riggs (1976), who describes a simplified slope-area method (Dalrymple and Benson, 1967) for estimation of peak discharge in natural channels also in the Pacific Northwest. For low-gradient, sand-bedded streams in the southeastern plains of the United States, Sefick and others (2015) present concepts similar to those provided in this assessment of hydraulic properties of streams in Texas. Sefick and others (2015) developed an equation in the general form of Manning's equation (Sturm, 2010) to estimate channel discharge using channel geometry, where Q (discharge) is log-log proportional to A (cross-section area), Rh (hydraulic radius), and S (energy slope). Sefick and others (2015) considered 484 direct measurements of discharge for 81 streams and statistically related the measured discharge to cross-section area, hydraulic radius, and bed slope.

The Sefick and others (2015) report is notable, because those authors used a nonparametric bias correction for the logarithmic retransformation of parameters in their equation. Sefick and others (2015, p. 1064) provided an algebraic equation of the correction factor they used, which appears to be the Duan bias correction (Helsel and Hirsch, 2002, p. 256–257). The Duan bias correction is further discussed in the section titled "Retransformation Bias Correction" in this report.

For 15 streamgages in the Brazos and Sabine River Basins of Texas, Heitmuller and Greene (2009) visually depict historical cross sections by using data from USGS field notes and hydraulic properties and those authors advocate that historical cross sections and hydraulic properties are useful for detecting geomorphic and hydraulic changes associated with instream habitat condition and function. Heitmuller and Greene (2009) recovered information from the discharge measurement, such as individual records of depth in cross sections, in order to describe geomorphic associations and properties of some segments of the Brazos, Sabine, and Trinity River Basins in Texas (fig. 1).

Heitmuller and others (2015) describe how abrupt downstream changes in surface lithology and associated sedimentary inputs coupled with extreme year-to-year annual peak discharge variability exert considerable controls on the hydraulic geometry of the Llano River channel in parts of central Texas, whereas more frequently occurring high flows (about the 1.5-year return period) mobilize bed sediment and temporarily modify bar deposits within the channel (Heitmuller and Asquith, 2008; Heitmuller, 2011; Heitmuller and others, 2015). Another Texas-based study by Coffman and others (2011) presents a geomorphic-unit classification scale that differentiates geomorphic units of a riverine system on the basis of their location either outside or inside the river channel. The geomorphic properties of a river system determine the distribution and type of potential habitat both within and adjacent to the channel.

Messinger (2009) developed regional regression equations (referred to by that author as "regional curves") for streams in the Appalachian Plateau of West Virginia and estimated that return periods associated with bankfull discharge ranged from 1.2 to 1.7 years on the basis of streamgage-specific frequency analyses. Messinger (2009, p. 1) attributes the following definition of regional curves to Dunne and Leopold (1978), explaining that they are "regression equations that quantify relations within a region between bankfull channel characteristics and [watershed area], and in some cases, other basin characteristics. They are used in natural channel design, which is a set of methods for restoring, rebuilding, or rerouting stream channels. Natural-channel design practitioners use regional curves to design channels or to verify identification of bankfull features in reference reaches." In total, 37 gaged and ungaged stream sites for the West Virginia study area were considered. The Messinger (2009) study was based on a combination of statistical analyses of discharge data, field-based surveying, and limited hydraulic computations for bankfull discharge.

Through an ensemble of four equations, Dutnell (2000) presents regional regression equations of bankfull discharge, cross-section area, top width, and hydraulic depth for Oklahoma as functions of watershed area and other cofactors, namely stream type (six types), river basin (seven basins), mean annual precipitation (three classes), ecoregion (four regions), and climate zone (four zones). The Dutnell (2000) study is considered in detail herein because of the geographic proximity of the study area to Texas. The study considered data obtained from 48 streamgages (40 in Oklahoma, 3 in Kansas, 2 in Missouri, and 3 in Texas) with field-based surveying of cross section and channel profiles to identify and compute basic hydraulic properties of bankfull conditions. Bankfull discharges were generally acquired by reviewing individual USGS stage-discharge rating curves in order to identify a change in slope in the rating that corresponds to bankfull conditions (U.S. Geological Survey, 2015d).

Further statistical analyses of the annual peak discharge data for the streamgages were made to determine whether the return period of bankfull discharge seems to generally exist in timeframes of 1.5 to 2 years. Dutnell (2000, p. 90) reports that the return period associated with bankfull discharge ranged from about 1.01 to 3.65 years with a central tendency of about 1.4 years.

A return period of 1.01 years equates to about the 1-percent cumulative probability from the left tail (low magnitude) of the peak discharge frequency distribution. Therefore, at least one of the bankfull discharge estimates in Dutnell (2000) represents a rare low-flow event such as the annual peak discharge during substantial drought conditions. Dutnell (2000, p. 20) used USGS annual peak discharges, rather than peak discharges derived from partial duration records (Langbein, 1949; Stedinger and others, 1993, p. 18.37–18.39). The details of analysis are unstated in Dutnell (2000) but likely included the log-Pearson type III distribution fit to annual peak discharge data. The log-Pearson type III distribution is the common theoretical distribution for flood analysis adopted for general use by Federal agencies (Linsley and others, 1982). The log-Pearson type III distribution, through the use of logarithms, low-outlier thresholds, method of moments, and other features, is intended for fitting in the right tail (flood flow) of the annual peak discharge distribution (Interagency Advisory Committee on Water Data, 1982; Veilleux and others, 2014). The uncertainty associated with computing bankfull discharge for return periods less than 2 years by using the log-Pearson type III distribution methods would be difficult to quantify and is subject to relatively larger amounts of uncertainty compared to discharges with return periods greater than 2 years.

A data-related constraint like the one mentioned in Dutnell (2000) also exists for this assessment. The constraint is that there are no partial-duration series of peak discharges for individual streamgages in Texas available for analysis, and perhaps more importantly, specific modeling of the left tail of the peak discharge frequency distribution for Texas hydrology is not available in sources such as Asquith and Slade (1997), Asquith (2001), Asquith and Thompson (2008), and Asquith and Roussel (2009).

Dutnell (2000) provides numerous regression equations for estimation of basic hydraulic properties based on watershed areas in Oklahoma. These equations are focused on watershed area being the predictor variable in a single variate context, but Dutnell (2000) acknowledges that other co-factors exist, such as mean annual precipitation or ecoregion. The Texas-based study documented herein focuses on multiple predictor variables as suggested by Asquith and others (2013) and Asquith (2014). The equations in Dutnell (2000) for “Oklahoma Region 1,” approximately the part of Oklahoma east of the 100th meridian, are reproduced in figure 4 herein. “Oklahoma Region 1” is defined in Dutnell (2000) by the locations of streamgages used, but the report does not geographically depict this region; hence, “Oklahoma Region 1” is not depicted in figure 1 herein. After applying screening criteria, Dutnell’s study (2000) ultimately included discharge measurements from 41 of the 48 streamgages originally considered. For the large geographic area that the author assessed in the study (Dutnell, 2000), discharge measurements from 41 streamgages represent a small sample size; the part of Oklahoma east of approximately the 100th meridian includes most of the State. Small sample sizes inherently result in considerable uncertainty in regression coefficients (Helsel and Hirsch, 2002), which partly explains why Dutnell (2000) limited equations to the domain of a single predictor (fig. 4) because the sample size was not large enough to include additional predictors.

Lastly, Dutnell (2000, p. 17–18) identifies several potential predictor variables that could be useful for regionalization studies of hydraulic properties. These include dominant bed material; entrenchment ratio, defined as the ratio of the width of the flood-prone area to the bankfull width; and sinuosity ratio. Dominant bed material and entrenchment ratio were not available for this assessment, so of those potential predictor variables, only sinuosity ratio is considered. Dutnell (2000, p. 6) defines sinuosity as “the ratio of channel length to valley length (straight-line distance),” where channel length refers to the main channel.

Computation of Summary Statistics From Hydraulic and Watershed Properties

For most discharge measurements (where discharge is symbolically represented as Q), the following hydraulic properties are available: cross-section area (A), water-surface top width (B), and reported mean velocity (V). Statewide summary statistics were computed by using these four hydraulic properties (Q, A, B, and V) and the following five watershed properties: (1) watershed area (contributing drainage area), (2) a multiple of main-channel slope (1,000 times main-channel slope), (3) mean annual precipitation, (4) drainage density, and (5) sinuosity ratio. The summary statistics of the hydraulic and watershed were

Dutnell (2000) "Oklahoma Region 1" Regional Regression Equations—The equations defining "regional curves" for "Oklahoma Region 1" (Dutnell's term referring to regression equations for the part of Oklahoma east of approximately the 100th meridian) are

$$Q_{\mathrm{Dut}} = 174.66\,W^{0.458} \quad \text{R-squared} = 0.80 \quad \text{Dutnell (2000, eq. 6),}$$
$$A_{\mathrm{Dut}} = 44.59\,W^{0.420} \quad \text{R-squared} = 0.77 \quad \text{Dutnell (2000, eq. 8),}$$
$$B_{\mathrm{Dut}} = 15.74\,W^{0.333} \quad \text{R-squared} = 0.83 \quad \text{Dutnell (2000, eq. 10), and}$$
$$D_{\mathrm{Dut}} = 2.76\,W^{0.089} \quad \text{R-squared} = 0.18 \quad \text{Dutnell (2000, eq. 12),}$$

where "$\ldots_{\mathrm{Dut}}$" denotes a result from Dutnell (2000); Q is bankfull discharge, in cubic feet per second; W is contributing drainage area of the watershed, in square miles; A is cross-section area at bankfull conditions, in square feet; B is top width of the bankfull water surface, in feet; D is mean bankfull depth or hydraulic depth, in feet; and (nonadjusted) R-squared is the coefficient of determination (Helsel and Hirsch, 2002; Faraway, 2005). The sample size (n) for the listed equations is not explicitly stated in Dutnell (2000) but is about 41 discharge measurements (Dutnell, 2000, fig. 12).

- Evidently not explicitly recognized by Dutnell (2000), the definition of hydraulic depth leads to another hydraulic depth representation ($D^\star$):

  $$D^\star = \frac{A_{\mathrm{Dut}}}{B_{\mathrm{Dut}}} = \frac{44.59\,W^{0.420}}{15.74\,W^{0.333}} = 2.83\,W^{0.087}.$$

  By algebraic inspection, D_{Dut} is approximately equal to $D^\star$. Dutnell (2000, p. 36) notes that R-squared for "mean bankfull depth versus drainage area is the lowest value observed, indicating more scatter in the data."

- The regionalization of D values is possibly best achieved as the ratio of predicted A and B (ratio of the methods [equations] for their estimation) as shown in the context of $D^\star$. The authors of the current (2020) study note that values of D were useful for quality-control and quality-assurance purposes.

- The Dutnell (2000) regional curves are shown herein to support later comparison to analogous regional curves by ecoregion in Texas.

Figure 4. Regression equations for "Oklahoma Region 1" by Dutnell (2000) with discussion pertinent to this assessment of hydraulic properties in streams for Texas.

computed for 372 selected streamgages in Texas (table 1), and these 372 streamgages and their data constitute the subsetted measurements dataset described in this report. Eight of the 10 ecoregions in Texas are represented in the statewide summary statistics. The High Plains and Trans Pecos ecoregions are not represented for reasons described in the Texas Ecological Regions (Ecoregions) section of this report.

The relation between Q, A, and V is $Q = A \times V$, and the relation between hydraulic (mean) depth (D), A, and B is $D = A / B$. Because D is computed from other hydraulic properties directly measured in the field as part of a discharge measurement, it does not represent a distinct hydraulic property containing new information, but it was useful for purposes of data screening in this report.

Hydraulic radius (Rh), another common hydraulic property of open-channel flow (Sturm, 2010), is mentioned here because some of the studies cited in this report have included Rh in their analyses. Rh is computed as the ratio of A to the wetted perimeter in the open channel. The wetted perimeter can be computed from the original field notes for a discharge measurement. Whereas the USGS discharge-measurement database provides the four hydraulic properties computed from field notes, it does not provide values for Rh or the wetted perimeter of the channel.

For this report, bankfull discharge conditions are assumed to be identifiable for a given stream location for which the results of this assessment are applied. This is an important assumption because bankfull discharge conditions are the conceptual basis for assessment of geomorphology and channel stability in many riverine situations. Hydraulic characteristics at bankfull conditions were not measured in the field. However, a working definition of a bankfull channel by Messinger (2009, p. 4) might be useful for context:

> The bankfull channel was defined as that part of the stream channel below the most distinct feature between the estimated elevations of the 1.1-year peak streamflow and the 2.0-year peak streamflow. Features used as indicators of the bankfull channel include, in order of preference and frequency used, rounded, vegetated, convex slope changes; bank substrate changes, particularly the edge of topsoil; sharp convex slope changes or those that showed other signs of instability; concave slope changes; and the elevation of an apparent floodplain.

Hill and others (1991), however, noted that there was no consensus on the return interval of bankfull discharge or of the discharge that constitutes a channel-forming discharge. Hill and others (1991) reported estimates for the return interval of bankfull discharge ranging from 1 to 32 years and concluded that bankfull discharge must be evaluated for each specific stream (Wolman and Miller, 1960; Leopold and Emmett, 1983; Chorley and others, 1984; Platts and others, 1985).

Regardless of how it is determined, bankfull discharge as reported by Mulvihill and others (2009, p. 2) is important "because it is considered to be the most effective flow for moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphological characteristics of channels." Biedenharn and others (2000, p. viii) offer

Table 1. Statewide summary statistics of four hydraulic and five watershed properties at 372 selected U.S. Geological Survey streamgages in Texas.

[Hydraulic properties for 4,629 discharge measurements consist of cross-section area, water-surface top width, discharge, and mean velocity. These measurements form the subsetted measurements dataset described within this report. Watershed properties for the 372 selected streamgages consist of contributing drainage area, main-channel slope, mean annual precipitation, drainage density, and sinuosity ratio]

Hydraulic or watershed property	Units	Minimum	First quartile	Median	Arithmetic mean	Third quartile	Maximum	Used in regression analyses?
Cross-section area	Square feet	50.5	1,290	2,670	4,704	6,670	38,700	Yes
Water-surface top width	Feet	28.8	170	315	514	574	5,320	Yes
Discharge	Cubic feet per second	245	3,370	7,670	15,500	19,600	128,000	Yes
Mean velocity	Feet per second	0.54	1.96	2.98	3.28	4.33	11.40	Yes
Watershed area (contributing drainage area)	Square miles	2.31	120	395	2,819	1,521	39,340	Yes
1,000 times (main-channel slope)[1]	Dimensionless	0.14	0.71	1.43	1.91	2.41	10.00	Yes
Mean annual precipitation[2]	Inches	20.0	30.3	35.8	37.1	44.1	61.8	Yes
Drainage density	Miles per square mile	0.69	2.49	2.84	3.07	3.33	14.81	No
Sinuosity ratio	Dimensionless	1.06	1.43	1.62	1.68	1.84	7.77	No

[1]Multiplying the main-channel slope by 1,000 introduces an arbitrary constant offset that eliminates numerous leading zeros.

[2]For this analysis, the mean annual precipitation during 1981–2010 was used. Any authoritative source of mean annual precipitation for a suitably long period (perhaps 30 years) is sufficient.

the following summary of bankfull and channel-forming discharge:

> An alluvial river adjusts the dimensions of its channel to the wide range of flows that mobilize its boundary sediments. However, in many rivers it has been demonstrated that a single representative discharge can be used to determine a stable channel geometry. The use of a single representative discharge is the foundation of “regime” and “hydraulic geometry” theories for determining morphological characteristics of alluvial channels and rivers. This representative discharge has been given several names by different researchers including *dominant* discharge, *channel-forming* discharge, *effective* discharge, and *bankfull* discharge [italics in original]. This has led to some confusion. In this report the channel-forming discharge and the dominant discharge are equivalent and are defined as a theoretical discharge that if maintained indefinitely would result in the same channel geometry as the existing channel is subject to the natural range of flow events. Although conceptually attractive, this definition is not necessarily physically feasible, because bankline vegetation, bank stability and even the bed configuration would be different in a natural stream than in a constant discharge stream. Channel-forming discharge concepts are applicable to stable stream systems, that is, streams that are neither aggrading nor degrading.

The term “alluvial river” is inherently ambiguous when applied across the broad spectrum of stream and river reaches in a State as large and climatologically diverse as Texas.

Finally, for the purposes of this report, conditions of bankfull discharge are assumed to be approximated by a discharge interval centered on the estimated median annual peak discharge. A rigorous assessment of this fundamental assumption was not made; such an assessment would entail an exhaustive review of many site surveys and copious field data. For a large regional assessment such as this one, evaluating the bankfull discharge for each stream as proposed by Hill and others (1991) is not possible.

Texas Ecological Regions (Ecoregions)

Researchers have demonstrated that the hydraulic properties of streams can differ by ecoregion (Heitmuller and Williams, 2006). On its Science Inventory website, the U.S. Environmental Protection Agency (2017) cites Griffith and others (2004) and defines and summarizes the usefulness of ecoregions as follows:

> Ecoregions denote areas of general similarity in ecosystems and in the type, quality, and quantity of environmental resources. They are designed to serve as a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components. Ecoregions are directly applicable to many state agency activities, including the selection of regional stream reference sites * * *.”

The 10 ecoregions in Texas were first published in 1960 (Gould and others, 1960) and were updated in 1975 (Gould, 1975). Texas Parks and Wildlife Department (2015) provides an online version of an ecoregion map modified from Gould and others (1960), as well as detailed descriptions of each ecoregion (Texas Parks and Wildlife Department, 2017). These ecoregions have subsequently been digitally adapted by the Missouri Resource Assessment Partnership, which processes geospatial data for natural and cultural resource management in Texas and other states (Missouri Resource Assessment Partnership, 2015). The 10 ecoregions in Texas, listed in alphabetical order, are Blackland Prairie, Cross Timbers, Edwards Plateau, Gulf Prairies, High Plains, Piney Woods, Post Oak Savannah, Rolling Plains, South Texas Plains, and Trans Pecos (fig. 1). Ecoregions are used herein as cofactors in regression analyses represented as categorical variables. The ecoregions represent a combination of physiography, soils, bedrock geology, vegetation, and climate, and they have been used to support studies in various scientific disciplines. Summary statistics of the four hydraulic properties that were incorporated into the regression analyses are listed in table 2 for 8 of the 10 ecoregions that ultimately were used in ecoregion-specific regression analyses. Regression analysis is thoroughly described by Faraway (2005, 2006) and Helsel and Hirsch (2002).

The High Plains and Trans Pecos ecoregions were excluded from the regression analyses because of a scarcity of historical streamgages in these ecoregions and the attendant availability of discharge measurements residing within the streamgage-specific ranges of discharge (lower and upper criteria values) of interest. Further consideration of these two ecoregions is made in the section titled “Statewide Regional Regression Equations and Potential Applicability in the High Plains and Trans Pecos Ecoregions.” The eight included ecoregions are used as cofactors in regression analyses; in other words, these ecoregions are represented as categorical (explanatory) variables in statistical analyses. The relation between ecoregions and the four hydraulic properties in Texas can be tenuous in some instances, because many of the ecoregions have similar characteristics such as similar slope, annual rainfall, and climate. Some precepts of a general intuitive nature, however, are applicable to streams in Texas, such as the following: (1) mean velocities are typically slower in ecoregions characterized by relatively sinuous channels (for example, the Piney Woods) compared to the mean velocities in ecoregions characterized by relatively straight channels (for example, the Edwards Plateau); and (2) mean velocities are typically higher in ecoregions with relatively steep terrain where the channel substrate is composed of bedrock (for example, the Edwards Plateau) compared to the mean velocities in ecoregions with relatively flat terrain where the channel substrate is composed of sand (for example, the South Texas Plains and Rolling Plains).

Table 2. Summary statistics, by ecoregion, for four hydraulic and five watershed properties at 372 selected U.S. Geological Survey streamgages in Texas.

[Hydraulic properties for discharge measurements consist of cross-section area, water-surface top width, discharge, and mean velocity. Watershed properties consist of contributing drainage area, main-channel slope, mean annual precipitation, drainage density, and sinuosity ratio. Statistics are shown for eight ecoregions of Texas used in regression analyses]

Hydraulic or watershed property	Units or dimensions	Minimum	First quartile	Median	Arithmetic mean	Third quartile	Maximum	Used in regressions for this study?
Blackland Prairie ecoregion (includes 65 streamgages and 720 discharge measurements)								
Cross-section area	Square feet	50.5	992	2,030	3,261	4,075	26,600	Yes
Water-surface top width	Feet	28.8	141	223	436	429	5,320	Yes
Discharge	Cubic feet per second	245	2,985	6,370	10,552	14,150	76,200	Yes
Mean velocity	Feet per second	0.62	2.38	3.25	3.49	4.43	9.06	Yes
Watershed area (contributing drainage area)	Square miles	2.31	48	189	1,368	805	20,870	Yes
1,000 (main-channel slope)	Dimensionless	0.283	1.379	2.298	2.694	3.230	8.919	Yes
Mean annual precipitation[1]	Inches	29.5	34.6	36.5	36.9	39.0	46.9	Yes
Drainage density	Miles per square mile	0.92	2.61	2.96	2.96	3.36	4.96	No
Sinuosity ratio	Dimensionless	1.08	1.38	1.55	1.60	1.74	3.63	No
Cross Timbers ecoregion (includes 47 streamgages and 523 discharge measurements)								
Cross-section area	Square feet	134.0	1,175	2,310	3,066	4,135	17,800	Yes
Water-surface top width	Feet	40.0	133	225	315	405	1,670	Yes
Discharge	Cubic feet per second	743	4,280	7,810	12,472	17,000	85,600	Yes
Mean velocity	Feet per second	0.79	2.98	3.88	4.06	4.87	8.57	Yes
Watershed area (contributing drainage area)	Square miles	33.3	260	479	2,930	2,208	17,680	Yes
1,000 (main-channel slope)	Dimensionless	0.343	0.984	1.808	2.029	2.514	6.652	Yes
Mean annual precipitation[1]	Inches	27.7	32.0	34.5	33.6	35.3	40.7	Yes
Drainage density	Miles per square mile	2.03	2.68	3.07	3.10	3.41	4.43	No
Sinuosity ratio	Dimensionless	1.06	1.42	1.71	1.80	1.91	3.97	No
Edwards Plateau ecoregion (includes 40 streamgages and 381 measurements)								
Cross-section area	Square feet	91.9	826	1,400	2,285	2,840	12,600	Yes
Water-surface top width	Feet	41.0	147	223	276	367	808	Yes
Discharge	Cubic feet per second	338	2,880	5,980	11,040	14,000	70,800	Yes
Mean velocity	Feet per second	0.75	3.23	4.50	4.65	5.49	11.40	Yes
Watershed area (contributing drainage area)	Square miles	6.79	112	355	1,794	965	27,610	Yes
1,000 (main-channel slope)	Dimensionless	0.701	1.887	3.202	3.937	5.144	10.000	Yes
Mean annual precipitation[1]	Inches	20.0	28.7	32.4	31.1	34.7	37.3	Yes
Drainage density	Miles per square mile	1.87	2.62	2.82	3.23	3.32	8.59	No
Sinuosity ratio	Dimensionless	1.07	1.34	1.44	1.52	1.64	2.59	No
Gulf Prairies ecoregion (includes 47 streamgages and 823 measurements)								
Cross-section area	Square feet	279.0	1,170	2,980	5,108	9,060	20,100	Yes
Water-surface top width	Feet	53.0	140	312	462	473	5,100	Yes
Discharge	Cubic feet per second	658	2,570	6,310	19,290	28,350	118,000	Yes
Mean velocity	Feet per second	0.73	1.84	2.58	2.99	4.11	7.39	Yes

Table 2. Summary statistics, by ecoregion, for four hydraulic and five watershed properties at 372 selected U.S. Geological Survey streamgages in Texas.—Continued

[Hydraulic properties for discharge measurements consist of cross-section area, water-surface top width, discharge, and mean velocity. Watershed properties consist of contributing drainage area, main-channel slope, mean annual precipitation, drainage density, and sinuosity ratio. Statistics are shown for eight ecoregions of Texas used in regression analyses]

Hydraulic or watershed property	Units or dimensions	Minimum	First quartile	Median	Arithmetic mean	Third quartile	Maximum	Used in regres-sions for this study?
Gulf Prairies ecoregion (includes 47 streamgages and 823 measurements)—Continued								
Watershed area (contributing drainage area)	Square miles	16.1	63	145	3,854	635	35,770	Yes
1,000 (main-channel slope)	Dimensionless	0.198	0.562	0.711	0.771	0.922	2.186	Yes
Mean annual precipitation[1]	Inches	27.8	43.1	47.7	45.6	50.2	54.8	Yes
Drainage density	Miles per square mile	0.69	1.84	2.37	2.59	2.80	7.79	No
Sinuosity ratio	Dimensionless	1.15	1.38	1.51	1.54	1.69	2.37	No
Piney Woods ecoregion (includes 53 streamgages and 584 measurements)								
Cross-section area	Square feet	305.0	2,320	5,890	7,685	11,100	38,700	Yes
Water-surface top width	Feet	51.1	330	515	866	1,111	4,460	Yes
Discharge	Cubic feet per second	980	4,560	10,900	19,600	29,800	100,800	Yes
Mean velocity	Feet per second	0.54	1.46	2.09	2.50	3.55	6.35	Yes
Watershed area (contributing drainage area)	Square miles	15.4	128	376	2,742	2,259	39,340	Yes
1,000 (main-channel slope)	Dimensionless	0.140	0.371	0.820	0.982	1.309	2.948	Yes
Mean annual precipitation[1]	Inches	42.6	48.5	50.3	50.9	52.9	61.8	Yes
Drainage density	Miles per square mile	0.71	2.27	2.62	2.69	3.09	4.39	No
Sinuosity ratio	Dimensionless	1.18	1.49	1.71	1.86	1.99	7.77	No
Post Oak Savannah ecoregion (includes 45 streamgages and 726 measurements)								
Cross-section area	Square feet	139.0	2,540	6,060	7,301	10,400	34,700	Yes
Water-surface top width	Feet	39.0	296	440	649	792	2,980	Yes
Discharge	Cubic feet per second	672	5,992	17,150	25,478	38,880	128,000	Yes
Mean velocity	Feet per second	0.71	2.13	3.08	3.31	4.38	9.22	Yes
Watershed area (contributing drainage area)	Square miles	17.3	236	500	6,068	2,113	34,310	Yes
1,000 (main-channel slope)	Dimensionless	0.147	0.361	0.907	1.068	1.540	3.226	Yes
Mean annual precipitation[1]	Inches	29.8	38.3	40.8	40.3	43.4	48.5	Yes
Drainage density	Miles per square mile	1.61	2.53	2.82	2.76	3.01	3.59	No
Sinuosity ratio	Dimensionless	1.10	1.48	1.69	1.69	1.85	2.34	No
Rolling Plains ecoregion (includes 57 streamgages and 559 measurements)								
Cross-section area	Square feet	137.0	1,060	1,620	2,158	2,520	15,800	Yes
Water-surface top width	Feet	48.0	166	221	372	354	3,050	Yes
Discharge	Cubic feet per second	421	2,240	4,090	6,942	8,085	59,400	Yes
Mean velocity	Feet per second	0.86	1.86	2.47	2.98	3.95	8.86	Yes
Watershed area (contributing drainage area)	Square miles	13.0	244	937	1,796	2,086	14,630	Yes
1,000 (main-channel slope)	Dimensionless	0.408	1.027	1.572	1.917	2.358	8.167	Yes
Mean annual precipitation[1]	Inches	20.0	22.5	25.0	25.3	27.4	32.2	Yes
Drainage density	Miles per square mile	2.01	2.70	3.46	4.10	4.46	14.81	No
Sinuosity ratio	Dimensionless	1.19	1.54	1.74	1.75	1.93	2.39	No

Table 2. Summary statistics, by ecoregion, for four hydraulic and five watershed properties at 372 selected U.S. Geological Survey streamgages in Texas.—Continued

[Hydraulic properties for discharge measurements consist of cross-section area, water-surface top width, discharge, and mean velocity. Watershed properties consist of contributing drainage area, main-channel slope, mean annual precipitation, drainage density, and sinuosity ratio. Statistics are shown for eight ecoregions of Texas used in regression analyses]

Hydraulic or watershed property	Units or dimensions	Minimum	First quartile	Median	Arithmetic mean	Third quartile	Maximum	Used in regressions for this study?
South Texas Plains ecoregion (includes 18 streamgages and 314 measurements)								
Cross-section area	Square feet	470.0	2,035	4,020	5,592	7,920	22,100	Yes
Water-surface top width	Feet	97.0	210	459	731	1,138	2,105	Yes
Discharge	Cubic feet per second	938	5,145	9,460	11,880	15,780	40,400	Yes
Mean velocity	Feet per second	0.99	1.65	2.08	2.54	2.89	10.60	Yes
Watershed area (contributing drainage area)	Square miles	150	484	760	2,683	3,919	15,430	Yes
1,000 (main-channel slope)	Dimensionless	0.392	0.759	1.558	2.119	3.299	5.067	Yes
Mean annual precipitation[1]	Inches	21.8	24.5	26.0	26.0	26.9	29.5	Yes
Drainage density	Miles per square mile	1.69	2.51	2.80	2.92	3.06	5.34	No
Sinuosity ratio	Dimensionless	1.10	1.47	1.63	1.66	1.82	2.13	No

[1]For this analysis, the mean annual precipitation during 1981–2010 was used. Any authoritative source of mean annual precipitation for a suitably long period (perhaps 30 years) is sufficient.

Compilation of Discharge Measurement Data

Two sets of discharge measurements specific to the streamgages used in this report were aggregated. The first set is referred to as the "foundational measurements." The second set is referred to as the "subsetted measurements."

To assess statistical relations between the four hydraulic properties and selected watershed properties, discharge measurements and annual peak discharges from 424 streamgages in Texas (fig. 1) were initially compiled. The 424 streamgages were selected in an ad hoc manner on the basis of availability of watershed properties; streamgage type; channel properties, such as non-concrete lined channels; and availability of direct measurements of discharge, such as non-theoretical weir computations. The measurements at these 424 streamgages constitute the foundational measurements.

The selected streamgages and measurements are representative of continuous discharge monitoring activities in Texas through April 2015; the earliest available discharge measurement is from January 1902. The period of record and number of measurements within a given period varies greatly among the 424 streamgages considered. That is, there is substantial variation in discharge measurement counts and streamgage-specific discharge records in time and substantial data screening was applied in preparation for statistical analyses.

Data from 372 of the 424 streamgages that provided the foundational measurements ultimately were used in the statistical relations described in this report. The dataset specific to the 372 streamgages is the aforementioned subsetted measurements. The reduction in streamgage count from 424 to 372 is attributable to the data screening procedures described in the section of this report titled "Foundational Measurements." Annual peak discharge data are available from NWIS (U.S. Geological Survey, 2015c) and can be readily obtained by entering the USGS streamgage number—referred to as the site number—on the NWIS web interface for Texas.

Foundational Measurements

Data that compose the foundational measurements were extracted from discharge measurement records stored in the NWIS database (U.S. Geological Survey, 2015a). Substantial preprocessing of these data, for quality control and assurance purposes, was necessary to produce the foundational measurements. These data were combined with watershed and climatology data. Further details about aggregation of the foundational measurements for use in this report is described in this section.

Discharge Measurements

A retrieval of all discharge measurement records (U.S. Geological Survey, 2015a) was made in April 2015 from the USGS discharge-measurement database for the 424 streamgages in Texas that were used in this report. The period of record retrieved is streamgage-specific and difficult to succinctly summarize; it is best stated that there were not beginning date criteria or a single begin-date criterion. The periods of record through April 2015 were retrieved. The following summary statistics are given for the year value of the 103,158 measurements in the input of the companion software (Asquith and Wallace, 2020): minimum 1902, first quartile 1970, median 1989, third quartile 2002, and maximum 2015. The years listed for these summary statistics are relatively recent because many early- to mid-20th century measurements have never been entered into the discharge-measurement database.

The following data were used from the discharge-measurement records: discharge, cross-section area, top width, and reported mean velocity. Reported mean velocity is the velocity listed in the original data and was not recomputed for this report from the reported discharge and cross-section areas. Further descriptions of the USGS discharge-measurement database in Texas are provided by Asquith and others (2013) and Asquith (2014).

The retrieved discharge measurements were scrutinized and preprocessed as a quality-control step. After removal of records of missing discharge and zero-flow conditions, the compilation of the foundational measurements continued with emphasis on the counts of streamgages and measurement records:

1. A total of 150,769 direct (Turnipseed and Sauer, 2010) or indirect (Dalrymple and Benson, 1967) measurements of discharge were retrieved for the 424 streamgages.

2. A concerted effort was made to identify and remove all indirect discharge measurements; the goal of this step was to remove any measurements made on cross sections of developed channels. A total of 316 indirect measurements were identified and removed from further consideration, which reduced the number of discharge measurements to 150,453. Among the 316 removed measurements were discharge measurements identified as being made on a concrete (fixed) control, which is an instance of a measurement being made on a cross section of a developed channel and could represent weir-flow computations (a type of indirect measurement). Measurements that were made on a fixed control were identified by using “fuzzy keyword” matching (Friedl, 2002) of text in the “remarks” attribute that is part of each NWIS data record. The NWIS database (U.S. Geological Survey, 2015a) does not contain a single authoritative attribute for identification of all historical indirect measurements of discharge. That is, whether the discharge measurement was made by direct or indirect methods is not identified in a single attribute field for all historical measurements. USGS database data-entry portals currently (2020) provide an attribute that makes it possible to readily identify a given discharge measurement as an indirect measurement; however, this attribute cannot be relied on to cover the full history of most streamgages in Texas. In view of this complication, however, the remarks attribute appears to provide the most suitable large-scale retrospective mechanism for data filtering to identify measurements made by using indirect methods. Useful keywords for detecting an indirect measurement of discharge included “indirect,” “slope-area,” “contracted-width,” “V-notch” (a form of weir), or “compute(d) by weir.” Keywords for direct measurements not representative of a channel included “made at control” and “(in|on|at) weir,” where the symbol “|” means “or.” Unfortunately, not all keyword uses of “weir” should be excluded because weirs often regulate stream stage, or gage height, in the so-called control section when the actual direct measurements of discharge are made elsewhere near the streamgage.

Of the 150,453 measurements retained for further preprocessing, the following observations were made:

3. A total of 106,551 measurements have values entered for the four hydraulic properties of discharge (a given), cross-section area, top width, and mean velocity.

4. A total of 106,338 measurements have nonzero (meaning also nonnegative) values of discharge, cross-section area, top width, and mean velocity.

5. A total of 103,231 measurements have a computed ratio of discharge to cross-section area (a mean velocity) within 0.1 foot per second (ft/s) of the reported mean velocity—thus about 3,000 of the 106,338 measurements that have nonzero values of discharge, cross-section area, top width, and mean velocity were removed from further consideration, because it was perceived that there was insufficient internal numerical consistency.

6. A total of 103,158 discharge measurements appear to have been used by the USGS in streamgaging operations. There is a “used” (yes/no) attribute, and the justification for removal from consideration in this report is founded on the assumption that if USGS personnel flagged a measurement as “not used,” then some aspect of that measurement’s applicability for this report is likely questionable. For example, a discharge measurement might have an associated stage, or gage height, that is erroneous and thus the measured was flagged as “not used.”

Watershed Properties and Climatology

The foundational measurements were composed of the 103,158 records compiled for the 424 streamgages. These records contain various data attributes, including selected watershed properties (such as watershed area), climatology information (such as mean annual precipitation), Texas ecoregion, and the name of the county where the streamgage is located. The following seven watershed properties were investigated for possible use in this report:

7. *Watershed area (contributing drainage area)*—the contributing drainage area, in square miles, of the watershed monitored by the streamgage. Physically, this area is equal to or less than total drainage area, which is not reported here. The term "watershed area" is preferred for this report so that the symbol *W* can be used to represent this area as opposed to the symbol *A,* which is used to represent cross-section area.

8. *Mean annual precipitation*—the mean annual precipitation at the streamgage location during 1971–2000 (PRISM Climate Group, 2010).

9. *Standard deviation of the mean annual precipitation*—the standard deviation of the 30 individual annual precipitation values during 1971–2000 (PRISM Climate Group, 2010).

10. *Drainage density*—the ratio of the total length of streams in a watershed to the total area of the watershed in units of distance (miles) of channel per square mile (Cleveland and others, 2013). Drainage density was investigated but not used to compute the results shown in this report. Drainage density summary statistics are included for reference purposes only.

11. *Main-channel slope*—the dimensionless main-channel slope (Asquith and Roussel, 2007, 2009; Asquith and others, 2013), defined as the change in elevation, in feet, between the two endpoints of the main channel divided by the main-channel length, in feet, where the main channel is defined as the length in stream-course miles of the longest defined channel shown in a 30-meter digital elevation model from the approximate watershed headwaters to the outlet.

12. *Proximal-channel slope*—dimensionless channel slope proximal to a streamgage within 1 kilometer of the streamgage (Cleveland and others, 2013, p. 34; Asquith and Burley, 2013). Proximal slope was investigated but not used to compute the results shown in this report.

13. *Sinuosity ratio*—following Dutnell (2000, p. 6), "the ratio of the channel length of the main channel to valley length (straight-line distance)"; also see Cleveland and others (2013, p. 34) and Asquith and Burley (2013). The main channel is meant to represent the length from the streamgage upstream to the end of the longest channel; this typically is shorter than the longest flow path to the drainage divide. The sinuosity ratio was investigated but not used to compute the results shown in this report, but its summary statistics are included in tables 1 and 2 for reference purposes.

Regional Regression Equations for Estimation of Median Annual Peak Discharge

Asquith and Roussel (2009) present two suites of regression equations for estimation of annual peak discharge having selected return periods of 2, 5, 10, 25, 50, 100, 200, 250, and 500 years. These return periods are useful in the hydrologic design of infrastructure such as bridges and levees. The two suites of regression equations in Asquith and Roussel (2009) embody a unique set of continuous-variable predictor variables, such as watershed area, that are repeated (held constant) among an ensemble of response variables that represent hydraulic properties.

The statistical techniques for *T*-year return period estimation by Asquith and Roussel (2009) were focused on the right tail of the annual peak discharge distribution (flood flows). As discussed in the section titled "Discharge Measurements Considered Approximate to Bankfull Conditions (the Subsetted Measurements)," the efficacy of left tail estimation is inherently unknown for estimating return period events shorter than 2 years for this report. Asquith and Roussel (2009) developed equations based on a regional analysis of the relations between statistical attributes of different time series of annual peak discharge data for many hundreds of streamgages in Texas and watershed properties and additional predictor variables. The watersheds represented in the Asquith and Roussel (2009) equations were considered undeveloped, being relatively unaffected by urbanization or by regulation at upstream reservoirs at the time of annual peak discharge.

Three equations (Asquith and Roussel, 2009, table 3) using the OmegaEM parameter (Asquith and Roussel, 2009, figs. 2–4) were applied in this assessment, because the equations were deemed to have the least predictive error compared to analogous equations in Asquith and Roussel (2009, table 2) that differ only in predictor variables. The OmegaEM parameter is a generalized physiographic, terrain, and climate parameter that was developed by those authors to enhance prediction capabilities; this parameter also was used by Asquith and others (2013). A comprehensive listing of the three OmegaEM equations pertinent to this report is provided in figure 5. All of the parameters in the three OmegaEM equations are defined, diagnostic statistics of the regression equations are listed, and example computations are included to depict how these equations were used in the subsetting task (fig. 5). The three OmegaEM equations were applied during the subsetting of the foundational measurements and are not necessary for end-user application of the regression equations of hydraulic properties described in this report.

Regional Regression Equations—Selected equations (Asquith and Roussel, 2009, table 3) used for estimation of T-year recurrence interval peak discharge (Q_T), in cubic feet per second, where T-year represents the average recurrence interval, in years, over an extended period of time before peak discharge exceeds a given threshold (magnitude). Examples are provided for 2-, 5-, and 10-year recurrence intervals. The equations use watershed properties of mean annual precipitation (P), in inches; dimensionless main-channel slope (S); contributing drainage area (W), in square miles; and the dimensionless OmegaEM parameter (Ω; Asquith and Roussel, 2009, figs. 2–4). For this analysis, the mean annual precipitation during 1981–2010 was used. Any authoritative source of mean annual precipitation for a suitably long period (perhaps 30 years) is sufficient.

Asquith and Roussel (2009, table 3) equation	RSE	adjRsq
$Q_2 = P^{1.398} \cdot S^{0.270} \cdot 10^{[50.98-50.30W^{-0.0058}+0.776\Omega]}$	0.29	0.84
$Q_5 = P^{1.308} \cdot S^{0.372} \cdot 10^{[16.62-15.32W^{-0.0215}+0.885\Omega]}$	0.26	0.88
$Q_{10} = P^{1.203} \cdot S^{0.403} \cdot 10^{[13.62-11.97W^{-0.0289}+0.918\Omega]}$	0.25	0.89

Diagnostics shown are residual standard error (RSE), in units of $\log_{10}$(cubic feet per second) and adjusted coefficient of determination (adjRsq) (Helsel and Hirsch, 2002; Faraway, 2005).

Example Computation—The equation for the 2-year (median annual peak) discharge (Q_2) is

$$Q_2 = P^{1.398} \cdot S^{0.270} \cdot 10^{[50.98-50.30W^{-0.0058}+0.776\Omega]},$$

and consider a watershed with a streamgage monitoring discharge in a natural channel having $W = 737$ square miles, $P = 24.5$ inches, $S = 0.00326$, and $\Omega = 0.33$; the Q_2, in cubic feet per second (ft^3/s), thus is

$$Q_2 = (24.5)^{1.398} \cdot (0.00326)^{0.270} \cdot 10^{[50.98-50.30\,(737)^{-0.0058}+0.776 \cdot 0.33]} = 12{,}500 \text{ ft}^3/\text{s}.$$

Similarly, the other two T-year peak discharges are $Q_5 = 32{,}500$ and $Q_{10} = 50{,}300$ ft^3/s.

Example Interval Computation for Subsetting Discharge Measurements—Q_2, Q_5, and Q_{10} for the example streamgage provide for an computation of the interval considered in part to subset the measurements to those discharges thought to approximate median annual peak discharge. The lower (Q_{lo}) and upper (Q_{hi}) limits of the interval are

$$\begin{aligned}\log_{10}(Q_{\text{lo}}) &= \log_{10}(Q_2) - \log_{10}(Q_5/Q_2),\\ \log_{10}(Q_{\text{lo}}) &= \log_{10}(12{,}500) - \log_{10}(32{,}500/12{,}500) = 3.682, \text{and}\\ Q_{\text{hi}} &= Q_{10} = 50{,}300 \text{ ft}^3/\text{s},\end{aligned}$$

where $Q_{\text{lo}} = 10^{(3.682)} = 4{,}810$ ft^3/s and for shorthand, $\log(Q_5/Q_2) = Q_{\text{err}}$ (a "discharge error"). The triad Q_{lo}, Q_{hi}, and Q_{err} are used in figure 6. Given discharge measurement no. 076 (a sequence number) having a value $Q_{[\text{no.}\,076]} = 7{,}500$ ft^3/s is obviously in the interval

$$4{,}810 \le Q_{[\text{no.}\,076]} \le 50{,}300 \text{ ft}^3/\text{s},$$

and would be slated for later statistical analysis. However, the discharge for the next measurement $Q_{[\text{no.}\,077]} = 1{,}580$ ft^3/s would not, because $1{,}580 < Q_{\text{lo}}$. Only discharges within the interval and thus thought to approximate median annual peak discharge are retained.

Figure 5. Regional regression equations of selected annual peak discharge (Asquith and Roussel, 2009) and respective computation for an example U.S. Geological Survey streamgage as well as example computation to subset the U.S. Geological Survey discharge measurement database for this assessment.

Database of Sample Median and Standard Deviation of Observed Annual Peak Discharge

For each of the 424 streamgages, a time series of annual peak discharge data was compiled from the NWIS database for the period of record for each streamgage through the 2014 water year (U.S. Geological Survey, 2015b, c). A water year is the 12-month period beginning October 1 in a given year through September 30 of the following year, designated by the calendar year in which it ends. The total number of annual peak discharge measurements for all 424 streamgages is more than 21,200. (The peak discharge data are not reproduced in this report.) The sample median of untransformed data and standard deviation of the base-10 logarithmically transformed annual peak discharge at each streamgage were computed.

In the late stages of data preparation for statistical analysis, these peak discharge statistics were used in an algorithm used to subset the foundational measurements to those discharges considered approximate to median annual peak discharge, namely the subsetted measurements dataset. The subsetting algorithm or process is delineated in a pseudocode language style (fig. 6) and is discussed further in the section titled "Discharge Measurements Considered Approximate to Bankfull Conditions (the Subsetted Measurements)."

Discharge Measurements Considered Approximate to Bankfull Conditions (the Subsetted Measurements)

The foundational measurements were loaded into the R environment (R Development Core Team, 2015) for statistical analysis. This section provides a general overview of database subsetting and additional steps towards quality control and assurance. A general summary of the steps taken for subsetting follows:

1. Streamgages 07227500 and 07228000 were removed from the regression analysis and are not thus present in the regression equations in this report as per the following justification. Both streamgages are on the Canadian River in far northwestern Texas. The headwaters of the Canadian River are in New Mexico; the drainage basin for the Canadian River is much larger than other basins in this general region of the State, and the peak discharge characteristics of the Canadian River at streamgages 07227500 and 07228000 are dissimilar from the peak discharge characteristics of other streams in this part of Texas. Furthermore, historical temporal changes in the flow regime for these streamgages have been documented (Brauer and others, 2015). Removing streamgages 07227500 and 07228000 and their measurements reduces the number of streamgages to 422 and reduces the number of measurements to 100,551.
2. The subsetting of measurements considered approximate to bankfull conditions was made. Part of the approach is described with figure 5. The logarithm of the ratio between the 5-year and 2-year discharges was chosen, because it represents the two regional estimates in Asquith and Roussel (2009) with the shortest return periods. The result is a discharge interval centered on the estimated median annual peak discharge at a given site. There is not an equation specific to a return periods shorter than 2 years, and thus, an objective method to establish a lower limit of discharge was needed (fig. 5). The subsetting process of measurements considered approximate to bankfull conditions (fig. 6) reduces the number of streamgages to 377 and reduces the number of measurements to 4,703. This step removes more than 95 percent of the measurements that remained after the previous step, and thus it is by far the most important step in the database subsetting process prior to regression analyses of the data. The subsetting process (fig. 6) was developed through exploratory evaluation and considerable iteration. The optimality of the subsetting process for identification of discharges at bankfull conditions cannot be assessed. There is no means for independent verification of bankfull conditions without resorting to site-by-site field visitation and surveying.
3. The relation between cross-section area (A) and water-surface top width (B) was inspected through geometric computations of a square-equivalent shape of the channel (channel depth $H1$ equal to square root of A) and a parabolic shape of the channel (maximum channel depth $H2$ equal to $3/2 \times A/B$). A ratio of $H1/H2$ greater than 3/2 was set as a criterion for acceptance. Graphical inspection (not reported here) indicated that this criterion helps to remove potential erroneous values. This step reduces the number of streamgages by 1 to 376 and reduces the number of measurements to 4,681.
4. All measurements with a Froude number (Sturm, 2010) greater than or equal to one (unity) were removed. This criterion removes those discharge measurements projected as representing supercritical flow conditions. This step maintains the number of streamgages at 376 and reduces the number of discharge measurements to 4,678.
5. The empirical distribution of the Froude numbers for the 4,678 discharge measurements from the previous step was reviewed (distribution not included in this report), and measurements having Froude numbers less than the 0.1 percentile (Froude = 0.0416) or greater than the 99.9 percentile (Froude = 0.793) were removed. Visual inspection of the shape of the empirical distribution justified this decision, because 10 highly unusual measurements were removed. This step maintains the number of streamgages at 376 and reduces the number of measurements to 4,668.

Logic blocks {...}, vector-indexing blocks [...], verbs and conditions (**ifelse**, **isMissing**, **return**) and other keywords (**and**, **c** [concatenate], **foreach**, **in**, **log10**, **to**) are typeset in a green san serif typeface. In the listing, function arguments are denoted by opening and closing pairs of parentheses. Comments for further guidance are in *red italics*. A weighted mean of the two discharges is computed by **weightedMean**. Columns in a database are indicted by the `DATATABLE$Column` notation where the salient columns are defined as:

- `$Station` — streamgage identification numbers;
- `$MEDPEAK` — median annual peak discharges, which might not exist for some streamgages that are not operated as "full range" across the discharge spectrum;
- `$SDLOG` — standard deviations of the logarithms of annual peak discharge, which might not exist if all annual peak discharges are equal or if only one peak was available;
- `$QLO` — lower limit of discharge value for interval containing discharge thought to approximate median annual peak discharge Q_{lo} (fig. 5);
- `$QHI` — upper limit of discharge value for interval containing discharge thought to approximate median annual peak discharge Q_{hi} (fig. 5); and
- `$QERR` — Q_{err} terms (fig. 5).

```
D <- FoundationalDatabase # make a copy to D for syntax brevity
                          # in the 20 or so lines that follow:
n <- length(D$Station)    # how many streamgages
Qlo <- foreach i in (1 to n) do { # loop for every station and return n values
   return(D$QLO[i]) if isMissing(D$MEDPEAK[i])   # no median peak available
   twoQ <- c(log10(D$MEDPEAK[i]) - D$SDLOG[i],   # median - 1 standard deviation
             log10(D$QLO[i])) # base10 logarithm of 'low' discharge from the
                              # the Asquith and Roussel (2009) equations
   wgts <- c(D$SDLOG[i], D$QERR[i]) # 'variation' for the two discharges
   val  <- weightedMean(twoQ, weights=1/wgts)    # invert to form 'weights'
   return(ifelse(isMissing(val), D$QLO[i], val)) # trap if SDLOG was zero
}                                                # end of logic block
Qhi <- foreach i in (1 to n) do { # loop for every station and return n values
   return(D$QHI[i]) if isMissing(D$MEDPEAK[i])   # no median peak available
   twoQ <- c(log10(D$MEDPEAK[i]) + D$SDLOG[i],   # median - 1 standard deviation
             log10(D$QHI[i])) # base10 logarithm of 'low' discharge from the
                              # the Asquith and Roussel (2009) equations
   wgts <- c(D$SDLOG[i], D$QERR[i]) # 'variation' for the two discharges
   val  <- weightedMean(twoQ, weights=1/wgts)    # invert to form 'weights'
   return(ifelse(isMissing(val), D$QHI[i], val)) # trap if SDLOG was zero
}                                                # end of logic block
DU <- D # make a copy of the Foundational Database, DU = '<D>ata <U>sed'
DU <- DU[DU$Q >= Qlo and DU$Q <= Qhi, ] # SUBSELECT BY JOINT CONDITION
```

Figure 6. Pseudoprogramming language representing the process used to subset the foundational measurements of the U.S. Geological Survey discharge measurement database into the subsetted measurements used for subsequent statistical analysis.

6. The relation (not shown in this report) between watershed area and main-channel slope was visually reviewed for inconsistent pairings of these watershed properties. No inconsistent pairings were identified.

7. The relation (not shown in this report) between cross-section area (*A*) and water-surface top width (*B)* was visually reviewed for inconsistent pairings of these hydraulic properties. This step maintains the number of streamgages at 376 and reduces the number of measurements to 4,665.

8. The relation (not shown in this report) between hydraulic depth ($D = A/B$) and discharge (*Q*) was visually inspected for inconsistent pairings of these hydraulic elements. This step maintains the number of streamgages at 376 and reduces the number of measurements to 4,654.

9. The relation (not shown in this report) between *Q* and mean velocity (*V*) was visually reviewed for inconsistent pairings of these hydraulic elements. Measurements with mean velocities less than 0.5 ft/s were removed. This step maintains the number of streamgages at 376 and reduces the number of measurements to 4,651.

10. The remaining streamgages in the High Plains and Trans Pecos ecoregions were removed because of insufficient data. This step reduces the number of streamgages to 372 and reduces the number of measurements to 4,629.

The final dataset consisting of 4,629 discharge measurements from the 372 streamgages for the subsetted measurements was used for the regression analyses discussed in the section titled “Regional Regression Equations for Estimating Hydraulic Properties at Approximate Bankfull Conditions” of this report. Once the aforementioned criteria were applied, statewide (table 1) and ecoregion (table 2) summary statistics of hydraulic properties were computed.

Regional Regression Equations for Estimating Hydraulic Properties at Approximate Bankfull Conditions

Numerous regression equations were established herein to estimate the basic hydraulic properties of cross-section area (*A*), water-surface top width (*B*), discharge (*Q*), and mean velocity (*V*) as functions of selected watershed properties and ecoregion in Texas. Equations for these four hydraulic properties given unique sets of continuous-predictor variables represent an ensemble, meaning it is anticipated that *A*, *B*, *Q*, and *V* will be estimated together by end users for a given application.

In a general sense, regression equations to estimate *A* will be referred to as “*A*-regressions,” similarly, regression equations to estimate *B* will be referred to as “*B*-regressions,” and so forth. The references are then modified by various adjectives or phrases related to different Texas ecoregions or predictor variables that are included, such as the “Edwards Plateau *A*-regression based on watershed area and mean annual precipitation.”

For each hydraulic property, two separate types of regression analyses were made. First, separate regressions were computed for each of the eight ecoregions considered. The Rolling Plains *V*-regression, for example, only used discharge measurement data from streamgages in the Rolling Plains ecoregion. Second, combined or aggregated regional regressions were made for which discharge measurement data from all 372 streamgages were used; these aggregated regional regression equations treat ecoregion as a categorical variable. Such treatment yields eight ecoregion-specific regression coefficients, given the eight ecoregions considered. The aggregated regional regressions are equivalently termed “All Regions” in contrast to individual ecoregions in listings of regression coefficients presented in this report. Because the Blackland Prairie ecoregion is alphabetically first, it serves as the reference classification. Hence, the regression coefficient was zero for the Blackland Prairie ecoregion in all regressions using ecoregion as a categorical variable. Example computations are provided showing how these two types of regressions may be applied by using a selected regional equation as well as the aggregated regional equations (figs. 7 and 8).

The regression equations presented herein to estimate hydraulic properties in Texas are exclusively based on logarithmic transformation of both response and predictor variables. Other transformations for the response variables were explored (results not reported herein) by using Box-Cox methods (Box and Cox, 1964). The use of only logarithmic transformation for this analysis contrasts with analyses by Asquith and others (2013) and Asquith (2014) where a root transformation on mean velocity was found to be suitable (figs. 2 and 3). The exclusive use of logarithmic transformation for the response variables leads to the consideration of a retransformation bias correction, as discussed next.

Retransformation Bias Correction

When a response variable, such as a hydraulic property, is transformed into logarithmic units as part of the regression analysis, the retransformed response variable must be bias-corrected to obtain the arithmetic mean estimate (response) in the original units (Duan, 1983; Helsel and Hirsch, 2002, p. 256–257). Because logarithmic transformation exclusively was used for this assessment, a retransformation bias correction is appropriate in order to obtain an accurate estimate of a given hydraulic property and a simple retransformation bias correction known as the Duan bias correction needs reporting. Retransformation yields a median estimate of a hydraulic property rather than the arithmetic mean. Simply retransforming a log-transformed response will return a biased and therefore inconsistent estimate of the arithmetic mean.

Watershed Properties—An example watershed in the Cross Timbers ecoregion has a contributing drainage area (W) of 801 square miles, a dimensionless main-channel slope (S) of 0.0015, and a mean annual precipitation (P) of about 32 inches. For the ecoregion (table 2, "Cross Timbers"), the ranges of the variables are $[33.3 \leq W \leq 17{,}680]$ square miles, $[0.000343 \leq S \leq 0.00665]$ dimensionless, and $[27.7 \leq P \leq 40.7]$ inches. The given values are within these ranges, so the equations are judged applicable. For this analysis, the mean annual precipitation during 1981–2010 was used. Any authoritative source of mean annual precipitation for a suitably long period (perhaps 30 years) is sufficient.

Aggregate Regional Curves—The aggregate regional curves (table 4, "All Regions") for cross-section area (A), in square feet; top width (B), in feet; discharge (Q), in cubic feet per second; and mean velocity (V), in feet per second, using predictor variables of W and P are

$$\begin{aligned}
\log_{10}(A/1.19) &= 0.8425 + 0.3861\log_{10}(W) + 0.8975\log_{10}(P) - 0.0690,\\
\log_{10}(B/1.35) &= 0.7790 + 0.2118\log_{10}(W) + 0.6765\log_{10}(P) - 0.0886,\\
\log_{10}(Q/1.19) &= 0.5779 + 0.4695\log_{10}(W) + 1.2461\log_{10}(P) - 0.0185, \text{ and}\\
\log_{10}(V/1.10) &= -0.2651 + 0.0833\log_{10}(W) + 0.3489\log_{10}(P) + 0.0505,
\end{aligned}$$

where the regression coefficients applicable to the ecoregion are shown on the right-hand side of the equations and the Duan bias corrections are shown as the denominators on the left-hand side of the equations. For example, the 1.35 shown within the B equation is the Duan bias correction. The additive term on the left of the right-hand side of the equation is the regression intercept, whereas the additive term of the far right is the categorical variable coefficient for this particular region. The solutions for the example watershed are

$$\begin{aligned}
A &= 2{,}094 && \text{square feet,}\\
B &= 304 && \text{feet,}\\
Q &= 7{,}478 && \text{cubic feet per second,}\\
V &= 3.92 && \text{feet per second (ft/s), and also consider that}\\
&= && Q/A = 7{,}478 \text{ cubic feet per second}/2{,}094 \text{ square feet} = 3.57 \text{ ft/s,}
\end{aligned}$$

which shows that two different velocities can be computed with the equations and information provided.

Figure 7. Example computations of aggregate regional regression equations for an example watershed in the Cross Timbers ecoregion of Texas.

Watershed Properties—An example watershed in the Cross Timbers ecoregion has a contributing drainage area (W) of 801 square miles, a dimensionless main-channel slope (S) of 0.0015, and a mean annual precipitation (P) of about 32 inches. For the ecoregion (table 2, "Cross Timbers"), the ranges of the variables are $[33.3 \leq W \leq 17{,}680]$ square miles, $[0.000343 \leq S \leq 0.00665]$ dimensionless, and $[27.7 \leq P \leq 40.7]$ inches. The given values are within these ranges, so the equations are judged applicable. For this analysis, the mean annual precipitation during 1981–2010 was used. Any authoritative source of mean annual precipitation for a suitably long period (perhaps 30 years) is sufficient.

Region-Specific Regional Curves—The region-specific regional curves (table 4, "Cross Timbers" rows) for cross-section area (A), in square feet; top width (B), in feet; discharge (Q), in cubic feet per second; and mean velocity (V), in feet per second, using predictor variables of W and P are

$$\begin{aligned}
\log_{10}(A/1.20) &= 0.3804 + 0.4030\log_{10}(W) + 1.1213\log_{10}(P),\\
\log_{10}(B/1.25) &= 0.8564 + 0.2654\log_{10}(W) + 0.4589\log_{10}(P),\\
\log_{10}(Q/1.24) &= -0.1430 + 0.4482\log_{10}(W) + 1.7500\log_{10}(P), \text{ and}\\
\log_{10}(V/1.08) &= -0.5269 + 0.0452\log_{10}(W) + 0.6311\log_{10}(P),
\end{aligned}$$

where the regression coefficients applicable to the ecoregion are shown on the right-hand side of the equations and the Duan bias corrections are shown as the denominators on the left-hand side of the equations. For example, the 1.25 shown within the B equation is the Duan bias correction. The solutions for the example watershed are

$$\begin{aligned}
A &= 2{,}077 \quad \text{square feet,}\\
B &= 260 \quad \text{feet,}\\
Q &= 7{,}689 \quad \text{cubic feet per second,}\\
V &= 3.87 \quad \text{feet per second (ft/s), and also consider that}\\
&= Q/A = 7{,}689 \text{ cubic feet per second}/2{,}077 \text{ square feet} = 3.70 \text{ ft/s,}
\end{aligned}$$

which shows that two different velocities can be computed with the equations and information provided.

Figure 8. Example computations of region-specific regression equations for an example watershed in the Cross Timbers ecoregion of Texas.

Duan (1983) derived a nonparametric estimator that requires only that the residuals be independent and homoscedastic (constant variance about the regression line). In the case of a log transformation, the correction factor involves retransforming the residuals in the original units and computing their mean. A prediction from a regression is then multiplied by the Duan bias correction. This correction is provided for each regression equation presented in this report, and example computations involving the correction are shown. Further background on log transformation is available in Helsel and Hirsch (2002, p. 256–260).

Estimates of a hydraulic property using the regression equations in this report that are unbiased in the transformed scale will be biased upon retransformation to the original scale. The form of the bias correction factor depends on the transformation used in the regression analysis. In the literature relating hydraulic properties to watershed properties, the use of retransformation bias corrections is seldom discussed, although Sefick and others (2015, p. 1064) is an exception.

Whether a retransformation bias correction should be applied to parameters derived from the regression equations is an open question. For this report, it is suggested that retransformation bias corrections should be applied in most circumstances, because estimates of hydraulic properties from the regional regression equations could, in turn, be recombined through multiplication with other properties. The importance of this distinction is illustrated by the following example. Presume that an engineering design (a design target) mean velocity V exists for a location (perhaps dependent on the type of channel aggregate/substrate in the engineering design) and that the regional regression for cross-section area is used to estimate A, then an unbiased estimate of discharge Q would be $Q = z \times A \times V$, where z is the bias correction factor for the A-regression that has been explained within this section. This conceptual example differs from using a regional equation to estimate Q directly—the two estimates will not be numerically identical.

Regional Regression Equations and Associated Regression Diagnostics, With Examples From Selected Ecoregions

Regional equations to predict hydraulic properties are constructed by using multiple-linear regression analysis. The response variables in the regression equation are the hydraulic properties, and the predictor variables are watershed properties and ecoregion. In general, as watershed size increases discharge increases (Asquith and Thompson, 2008), regional equations as functions of watershed size were first developed and evaluated because of their simplicity. For this report, ecoregion also was simultaneously incorporated with watershed area to form ensembles of equations defining aggregated regional regression equations. The predictor variables of mean annual precipitation and main-channel slope then successively were included to create other equation ensembles reported herein. Diagnostics for the regression equations for individual ecoregions can depart substantially from the diagnostics for the regression equations for the aggregated ecoregion versions.

Regional regression equations for A, B, Q, and V were computed as functions of watershed area and ecoregion as well as by aggregating the data for the different ecoregions as a single categorical variable (the “All Regions” equations). Regression coefficients, bias correction along with regression diagnostics such as Nash-Sutcliffe efficiency, adjusted R-squared, and residual standard error and other information for regression as functions of watershed area, main-channel slope, and mean annual precipitation are presented in tables 3–5. In total, nine regression equations (applicable to eight individual ecoregions and one aggregate of ecoregions) for each of the four hydraulic properties were developed for three distinct combinations of watershed properties as predictor variables; thus, 108 regression equations (108 = 9 × 4 × 3) result from this ecoregion-inclusive study. An additional 12 statewide regression equations are presented for combinations of predictor variables but explicitly lack ecoregion. Discussion of all 120 equations is presented with interpretation of selected diagnostics and example computations.

Regression diagnostics reported for the aforementioned equations and others that follow in subsequent sections are Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970), adjusted R-squared (coefficient of determination; Helsel and Hirsch, 2002; Faraway, 2005), residual standard error (RSE; Helsel and Hirsch, 2002; Faraway, 2005), standard deviation of response variable (VARsd), and Akaike Information Criterion (AIC; Faraway, 2005). The NSE, expressed as a percentage in this report, is reported because it is a means to assess the predictive power of regression equations and is familiar to many hydrologists. The adjusted R-squared and RSE also are common regression diagnostics. Unlike the unadjusted R-squared value that increases with each additional explanatory variable added to a regression equation, the adjusted R-squared value includes a penalty for the use of more explanatory variables. This penalty ensures that the adjusted R-squared value increases only when the addition of an explanatory variable improves the regression equation more than would be expected by chance. As a result, the adjusted R-squared value tends to be a better indicator of the predictive capability of the regression equation compared to the unadjusted R-squared value (Helsel and Hirsch, 2002). RSE is a measure of remaining uncertainty of the response variable, whereas the standard deviation of the response variable is a measure of original uncertainty subject to explanation by a regression equation (Helsel and Hirsch, 2002).

RSE and VARsd are listed to communicate information about the variation in the original data relative to general variation of the regression equations. For example, the VARsd of A for the A-regression for the Cross Timbers ecoregion as a function of watershed area (table 3) is about 0.381 log10 ft/s, whereas the RSE of the A-regression is 0.267 log10 ft/s; this is a change of about −30 percent (100 × [0.267 − 0.381]/0.381 = −29.9). An RSE of 0.267 log10 ft/s is nearly one-third of a logarithmic cycle.

Table 3. Regression coefficients, diagnostics, bias correction, and other information for regional regression equations as functions of watershed area for estimation of four hydraulic properties of discharge measurements considered approximate to bankfull conditions in different ecoregions of Texas.

[NSE, Nash-Sutcliffe model efficiency coefficient; aRsq, adjusted coefficient of determination (adjusted R-squared); RSE, residual standard error in base-10 logarithmic units (log10) of respective response variable; VARsd, standard deviation of response variable; AIC, Akaike Information Criterion; Duan BC, Duan bias correction factor; Number of sites, number of U.S. Geological Survey streamgages; CDA, watershed area (contributing drainage area) based on square miles; MCS, dimensionless main-channel slope; MAP, mean annual precipitation based on inches per year; *A*, cross-section area, in square feet; *B*, water-surface top width, in feet; *Q*, discharge, in cubic feet per second; *V*, mean velocity, in feet per second. —, dimensionless; --, not applicable. The numeral "0" is truly zero for the Blackland Prairie based on regression approach to use ecological region as a categorical variable. Text in red is referenced directly in the report]

Hydraulic (response) variable	Ecological region or other spatial perspective	NSE	aRsq	RSE	VARsd	AIC	Duan BC	Number of sites	Number of measurements
		(Percent)	(log10)	(log10)	(log10)	(—)	(—)		
Cross-section area (*A*-regressions)	All Regions	70	0.697	0.256	0.465	528	1.190	372	4,629
	Blackland Prairie	61	0.606	0.300	0.478	314	1.290	65	719
	Cross Timbers	51	0.510	0.267	0.381	105	1.200	47	523
	Edwards Plateau	65	0.646	0.239	0.402	−5	1.170	40	381
	Gulf Prairies	77	0.767	0.230	0.477	−79	1.150	47	823
	Piney Woods	73	0.728	0.229	0.440	−58	1.160	53	584
	Post Oak Savannah	55	0.550	0.265	0.395	135	1.200	45	726
	Rolling Plains	46	0.462	0.240	0.327	−6	1.160	57	559
	South Texas Plains	62	0.622	0.241	0.392	1	1.160	18	314
Water-surface top width (*B*-regressions)	All Regions	35	0.346	0.321	0.397	2,631	1.360	372	4,629
	Blackland Prairie	27	0.268	0.366	0.428	600	1.520	65	719
	Cross Timbers	31	0.306	0.272	0.327	128	1.250	47	523
	Edwards Plateau	48	0.481	0.188	0.261	−188	1.090	40	381
	Gulf Prairies	33	0.325	0.319	0.388	460	1.400	47	823
	Piney Woods	24	0.242	0.354	0.407	450	1.380	53	584
	Post Oak Savannah	4	0.040	0.345	0.352	519	1.380	45	726
	Rolling Plains	30	0.298	0.279	0.334	165	1.260	57	559
	South Texas Plains	52	0.522	0.269	0.389	71	1.200	18	314
Discharge (*Q*-regressions)	All Regions	75	0.747	0.255	0.507	509	1.200	372	4,629
	Blackland Prairie	71	0.710	0.256	0.475	86	1.200	65	719
	Cross Timbers	52	0.521	0.286	0.414	180	1.250	47	523
	Edwards Plateau	54	0.536	0.321	0.471	220	1.320	40	381
	Gulf Prairies	86	0.855	0.225	0.592	−113	1.130	47	823
	Piney Woods	84	0.838	0.199	0.495	−224	1.120	53	584
	Post Oak Savannah	79	0.789	0.222	0.483	−123	1.140	45	726
	Rolling Plains	57	0.572	0.269	0.412	124	1.220	57	559
	South Texas Plains	34	0.340	0.286	0.351	108	1.260	18	314
Mean velocity (*V*-regressions)	All Regions	25	0.246	0.191	0.220	−2,176	1.100	372	4,629
	Blackland Prairie	2	0.021	0.186	0.188	−374	1.090	65	719
	Cross Timbers	2	0.020	0.178	0.180	−318	1.080	47	523
	Edwards Plateau	1	0.007	0.221	0.222	−64	1.120	40	381
	Gulf Prairies	40	0.400	0.160	0.206	−679	1.070	47	823
	Piney Woods	12	0.120	0.209	0.223	−165	1.120	53	584
	Post Oak Savannah	41	0.414	0.162	0.212	−578	1.070	45	726
	Rolling Plains	19	0.185	0.187	0.207	−287	1.100	57	559
	South Texas Plains	29	0.285	0.164	0.194	−241	1.080	18	314

Table 3. Regression coefficients, diagnostics, bias correction, and other information for regional regression equations as functions of watershed area for estimation of four hydraulic properties of discharge measurements considered approximate to bankfull conditions in different ecoregions of Texas.—Continued

[NSE, Nash-Sutcliffe model efficiency coefficient; aRsq, adjusted coefficient of determination (adjusted R-squared); RSE, residual standard error in base-10 logarithmic units (log10) of respective response variable; VARsd, standard deviation of response variable; AIC, Akaike Information Criterion; Duan BC, Duan bias correction factor; Number of sites, number of U.S. Geological Survey streamgages; CDA, watershed area (contributing drainage area) based on square miles; MCS, dimensionless main-channel slope; MAP, mean annual precipitation based on inches per year; *A*, cross-section area, in square feet; *B*, water-surface top width, in feet; *Q*, discharge, in cubic feet per second; *V*, mean velocity, in feet per second. —, dimensionless; --, not applicable. The numeral “0” is truly zero for the Blackland Prairie based on regression approach to use ecological region as a categorical variable. Text in red is referenced directly in the report]

Regression coefficients											
Continuous variable coefficients				Categorical variable coefficients							
Intercept (log10)	CDA (log10)	MCS (log10)	MAP (log10)	Blackland Prairie (log10)	Cross Timbers (log10)	Edwards Plateau (log10)	Gulf Prairies (log10)	Piney Woods (log10)	Post Oak Savanna (log10)	Rolling Plains (log10)	South Texas Plains (log10)
2.2373	0.3885	--	--	0	−0.1034	−0.1600	0.1199	0.2726	0.1271	−0.1996	0.0395
2.2246	0.3933	--	--	--	--	--	--	--	--	--	--
2.1258	0.3912	--	--	--	--	--	--	--	--	--	--
1.9395	0.4370	--	--	--	--	--	--	--	--	--	--
2.4003	0.3736	--	--	--	--	--	--	--	--	--	--
2.4001	0.4243	--	--	--	--	--	--	--	--	--	--
2.5272	0.3416	--	--	--	--	--	--	--	--	--	--
2.0879	0.3719	--	--	--	--	--	--	--	--	--	--
1.8824	0.5051	--	--	--	--	--	--	--	--	--	--
1.8303	0.2136	--	--	0	−0.1145	−0.0730	0.0286	0.2684	0.1003	−0.0624	0.1512
1.7742	0.2345	--	--	--	--	--	--	--	--	--	--
1.5707	0.2606	--	--	--	--	--	--	--	--	--	--
1.6682	0.2449	--	--	--	--	--	--	--	--	--	--
1.9033	0.1983	--	--	--	--	--	--	--	--	--	--
2.0566	0.2274	--	--	--	--	--	--	--	--	--	--
2.3813	0.0836	--	--	--	--	--	--	--	--	--	--
1.4918	0.3051	--	--	--	--	--	--	--	--	--	--
1.1468	0.4603	--	--	--	--	--	--	--	--	--	--
2.5145	0.4728	--	--	0	−0.0662	−0.0576	0.0273	0.0796	0.0298	−0.3062	−0.1668
2.6493	0.4228	--	--	--	--	--	--	--	--	--	--
2.5810	0.4298	--	--	--	--	--	--	--	--	--	--
2.4739	0.4668	--	--	--	--	--	--	--	--	--	--
2.4916	0.4902	--	--	--	--	--	--	--	--	--	--
2.4716	0.5127	--	--	--	--	--	--	--	--	--	--
2.4489	0.5003	--	--	--	--	--	--	--	--	--	--
2.0637	0.5207	--	--	--	--	--	--	--	--	--	--
2.8113	0.3358	--	--	--	--	--	--	--	--	--	--
0.2771	0.0843	--	--	0	0.0372	0.1023	−0.0926	−0.1929	−0.0974	−0.1067	−0.2065
0.4248	0.0295	--	--	--	--	--	--	--	--	--	--
0.4554	0.0386	--	--	--	--	--	--	--	--	--	--
0.5341	0.0299	--	--	--	--	--	--	--	--	--	--
0.0910	0.1167	--	--	--	--	--	--	--	--	--	--
0.0721	0.0882	--	--	--	--	--	--	--	--	--	--
−0.0788	0.1588	--	--	--	--	--	--	--	--	--	--
−0.0258	0.1492	--	--	--	--	--	--	--	--	--	--
0.9296	−0.1695	--	--	--	--	--	--	--	--	--	--

Table 4. Regression coefficients, diagnostics, bias correction, and other information for regional regression equations as functions of watershed area and mean annual precipitation for estimation of four hydraulic properties of discharge measurements considered approximate to bankfull conditions in different ecoregions of Texas.

[NSE, Nash-Sutcliffe model efficiency coefficient; aRsq, adjusted coefficient of determination (adjusted R-squared); RSE, residual standard error in base-10 logarithmic units (log10) of respective response variable; VARsd, standard deviation of response variable; AIC, Akaike Information Criterion; Duan BC, Duan bias correction factor; Number of sites, number of U.S. Geological Survey streamgages; CDA, watershed area (contributing drainage area) based on square miles; MCS, dimensionless main-channel slope; MAP, mean annual precipitation based on inches per year; *A*, cross-section area, in square feet; *B*, water-surface top width, in feet; *Q*, discharge, in cubic feet per second; *V*, mean velocity, in feet per second. —, dimensionless; --, not applicable. The numeral "0" is truly zero for the Blackland Prairie based on regression approach to use ecological region as a categorical variable. Text in red is referenced directly in the report]

Hydraulic (response) variable	Ecological region or other spatial perspective	NSE (Percent)	aRsq (log10)	RSE (log10)	VARsd (log10)	AIC (—)	Duan BC (—)	Number of sites	Number of measurements
Cross-section area (*A*-regressions)	All Regions	71	0.707	0.252	0.465	374	1.19	372	4,629
	Blackland Prairie	62	0.619	0.295	0.478	291	1.28	65	719
	Cross Timbers	52	0.519	0.264	0.381	96	1.20	47	523
	Edwards Plateau	65	0.645	0.239	0.402	−3	1.17	40	381
	Gulf Prairies	77	0.773	0.227	0.477	−100	1.15	47	823
	Piney Woods	73	0.728	0.229	0.440	−57	1.16	53	584
	Post Oak Savannah	67	0.666	0.228	0.395	−81	1.15	45	726
	Rolling Plains	50	0.503	0.231	0.327	−49	1.15	57	559
	South Texas Plains	65	0.645	0.233	0.392	−18	1.15	18	314
Water-surface top width (*B*-regressions)	All Regions	36	0.354	0.319	0.397	2,578	1.35	372	4,629
	Blackland Prairie	28	0.275	0.364	0.428	594	1.50	65	719
	Cross Timbers	31	0.307	0.272	0.327	128	1.25	47	523
	Edwards Plateau	49	0.484	0.188	0.261	−189	1.09	40	381
	Gulf Prairies	33	0.325	0.319	0.388	460	1.40	47	823
	Piney Woods	24	0.241	0.355	0.407	452	1.38	53	584
	Post Oak Savannah	34	0.336	0.287	0.352	253	1.24	45	726
	Rolling Plains	31	0.307	0.278	0.334	159	1.26	57	559
	South Texas Plains	58	0.582	0.252	0.389	30	1.18	18	314
Discharge (*Q*-regressions)	All Regions	76	0.763	0.247	0.507	205	1.19	372	4,629
	Blackland Prairie	72	0.715	0.254	0.475	73	1.20	65	719
	Cross Timbers	54	0.542	0.280	0.414	158	1.24	47	523
	Edwards Plateau	59	0.588	0.303	0.471	176	1.29	40	381
	Gulf Prairies	88	0.881	0.204	0.592	−273	1.12	47	823
	Piney Woods	84	0.841	0.197	0.495	−234	1.11	53	584
	Post Oak Savannah	81	0.810	0.211	0.483	−197	1.13	45	726
	Rolling Plains	58	0.578	0.267	0.412	117	1.22	57	559
	South Texas Plains	34	0.338	0.286	0.351	110	1.25	18	314
Mean velocity (*V*-regressions)	All Regions	25	0.253	0.190	0.220	−2,215	1.10	372	4,629
	Blackland Prairie	3	0.029	0.185	0.188	−379	1.09	65	719
	Cross Timbers	4	0.033	0.177	0.180	−324	1.08	47	523
	Edwards Plateau	22	0.210	0.198	0.222	−150	1.10	40	381
	Gulf Prairies	48	0.474	0.149	0.206	−788	1.07	47	823
	Piney Woods	13	0.126	0.209	0.223	−168	1.12	53	584
	Post Oak Savannah	51	0.507	0.149	0.212	−702	1.07	45	726
	Rolling Plains	21	0.207	0.184	0.207	−301	1.10	57	559
	South Texas Plains	36	0.357	0.155	0.194	−274	1.07	18	314

Table 4. Regression coefficients, diagnostics, bias correction, and other information for regional regression equations as functions of watershed area and mean annual precipitation for estimation of four hydraulic properties of discharge measurements considered approximate to bankfull conditions in different ecoregions of Texas.—Continued

[NSE, Nash-Sutcliffe model efficiency coefficient; aRsq, adjusted coefficient of determination (adjusted R-squared); RSE, residual standard error in base-10 logarithmic units (log10) of respective response variable; VARsd, standard deviation of response variable; AIC, Akaike Information Criterion; Duan BC, Duan bias correction factor; Number of sites, number of U.S. Geological Survey streamgages; CDA, watershed area (contributing drainage area) based on square miles; MCS, dimensionless main-channel slope; MAP, mean annual precipitation based on inches per year; *A*, cross-section area, in square feet; *B*, water-surface top width, in feet; *Q*, discharge, in cubic feet per second; *V*, mean velocity, in feet per second. —, dimensionless; --, not applicable. The numeral “0” is truly zero for the Blackland Prairie based on regression approach to use ecological region as a categorical variable. Text in red is referenced directly in the report]

Regression coefficients											
Continuous variable coefficients				Categorical variable coefficients							
Intercept (log10)	CDA (log10)	MCS (log10)	MAP (log10)	Blackland Prairie (log10)	Cross Timbers (log10)	Edwards Plateau (log10)	Gulf Prairies (log10)	Piney Woods (log10)	Post Oak Savanna (log10)	Rolling Plains (log10)	South Texas Plains (log10)
0.8425	0.3861	--	0.8975	0	−0.0690	−0.0781	0.0324	0.1338	0.1056	−0.0611	0.1779
−0.0082	0.3951	--	1.4268	--	--	--	--	--	--	--	--
0.3804	0.4030	--	1.1213	--	--	--	--	--	--	--	--
1.7904	0.4382	--	0.0990	--	--	--	--	--	--	--	--
1.2511	0.3758	--	0.6888	--	--	--	--	--	--	--	--
1.8821	0.4212	--	0.3074	--	--	--	--	--	--	--	--
−0.9227	0.2985	--	2.2673	--	--	--	--	--	--	--	--
0.5485	0.3404	--	1.1611	--	--	--	--	--	--	--	--
5.3179	0.4714	--	−2.3575	--	--	--	--	--	--	--	--
0.7790	0.2118	--	0.6765	0	−0.0886	−0.0113	−0.0373	0.1639	0.0840	0.0419	0.2555
0.2341	0.2358	--	0.9841	--	--	--	--	--	--	--	--
0.8564	0.2654	--	0.4589	--	--	--	--	--	--	--	--
1.3503	0.2477	--	0.2110	--	--	--	--	--	--	--	--
2.3510	0.1974	--	−0.2684	--	--	--	--	--	--	--	--
1.8547	0.2262	--	0.1198	--	--	--	--	--	--	--	--
−2.5290	0.0223	--	3.2270	--	--	--	--	--	--	--	--
0.7195	0.2892	--	0.5825	--	--	--	--	--	--	--	--
6.5112	0.4076	--	−3.6811	--	--	--	--	--	--	--	--
0.5779	0.4695	--	1.2461	0	−0.0185	0.0562	−0.0941	−0.1130	−0.0001	−0.1140	0.0254
1.1528	0.4241	--	0.9563	--	--	--	--	--	--	--	--
−0.1430	0.4482	--	1.7500	--	--	--	--	--	--	--	--
0.4449	0.4841	--	1.3464	--	--	--	--	--	--	--	--
−0.3385	0.4956	--	1.6963	--	--	--	--	--	--	--	--
1.0008	0.5037	--	0.8728	--	--	--	--	--	--	--	--
0.6566	0.4780	--	1.1779	--	--	--	--	--	--	--	--
1.2557	0.5041	--	0.6094	--	--	--	--	--	--	--	--
3.3131	0.3309	--	−0.3444	--	--	--	--	--	--	--	--
−0.2651	0.0833	--	0.3489	0	0.0505	0.1341	−0.1266	−0.2468	−0.1058	−0.0529	−0.1527
1.1617	0.0289	--	−0.4709	--	--	--	--	--	--	--	--
−0.5269	0.0452	--	0.6311	--	--	--	--	--	--	--	--
−1.3465	0.0459	--	1.2479	--	--	--	--	--	--	--	--
−1.5934	0.1199	--	1.0096	--	--	--	--	--	--	--	--
−0.8740	0.0824	--	0.5615	--	--	--	--	--	--	--	--
1.5806	0.1796	--	−1.0905	--	--	--	--	--	--	--	--
0.7081	0.1642	--	−0.5535	--	--	--	--	--	--	--	--
−2.0155	−0.1406	--	2.0209	--	--	--	--	--	--	--	--

Table 5. Regression coefficients, diagnostics, bias correction, and other information for regional regression equations as functions of watershed area, main-channel slope, and mean annual precipitation for estimation of four hydraulic properties of discharge measurements considered approximate to bankfull conditions in different ecoregions of Texas.

[NSE, Nash-Sutcliffe model efficiency coefficient; aRsq, adjusted coefficient of determination (adjusted R-squared); RSE, residual standard error in base-10 logarithmic units (log10) of respective response variable; VARsd, standard deviation of response variable; AIC, Akaike Information Criterion; Duan BC, Duan bias correction factor; Number of sites, number of U.S. Geological Survey streamgages; CDA, watershed area (contributing drainage area) based on square miles; MCS, dimensionless main-channel slope; MAP, mean annual precipitation based on inches per year; *A*, cross-section area, in square feet; *B*, water-surface top width, in feet; *Q*, discharge, in cubic feet per second; *V*, mean velocity, in feet per second. —, dimensionless; --, not applicable. The numeral “0” is truly zero for the Blackland Prairie based on regression approach to use ecological region as a categorical variable. Text in red is referenced directly in the report]

Hydraulic (response) variable	Ecological region or other spatial perspective	NSE	aRsq	RSE	VARsd	AIC	Duan BC	Number of sites	Number of measurements
		(Percent)	(log10)	(log10)	(log10)	(—)	(—)		
Cross-section area (*A*-regressions)	All Regions	71	0.707	0.252	0.465	373.2	1.19	372	4,629
	Blackland Prairie	62	0.619	0.295	0.478	292.2	1.28	65	719
	Cross Timbers	52	0.519	0.264	0.381	97.4	1.20	47	523
	Edwards Plateau	65	0.644	0.240	0.402	−1.1	1.17	40	381
	Gulf Prairies	78	0.780	0.223	0.477	−125.3	1.14	47	823
	Piney Woods	73	0.728	0.229	0.440	−56.6	1.16	53	584
	Post Oak Savannah	68	0.678	0.224	0.395	−106.8	1.15	45	726
	Rolling Plains	51	0.507	0.230	0.327	−52.5	1.15	57	559
	South Texas Plains	69	0.685	0.220	0.392	−54.3	1.13	18	314
Water-surface top width (*B*-regressions)	All Regions	36	0.354	0.319	0.397	2,579.5	1.35	372	4,629
	Blackland Prairie	28	0.274	0.365	0.428	595.6	1.50	65	719
	Cross Timbers	33	0.325	0.269	0.327	115.4	1.23	47	523
	Edwards Plateau	49	0.486	0.187	0.261	−189.9	1.09	40	381
	Gulf Prairies	36	0.352	0.313	0.388	427.8	1.38	47	823
	Piney Woods	25	0.242	0.354	0.407	451.6	1.38	53	584
	Post Oak Savannah	34	0.335	0.287	0.352	254.4	1.24	45	726
	Rolling Plains	37	0.362	0.266	0.334	113.3	1.23	57	559
	South Texas Plains	64	0.640	0.234	0.389	−16.1	1.16	18	314
Discharge (*Q*-regressions)	All Regions	77	0.773	0.241	0.507	−6.6	1.18	372	4,629
	Blackland Prairie	72	0.715	0.254	0.475	75.0	1.20	65	719
	Cross Timbers	59	0.586	0.266	0.414	105.5	1.21	47	523
	Edwards Plateau	60	0.598	0.299	0.471	167.2	1.29	40	381
	Gulf Prairies	89	0.886	0.200	0.592	−305.2	1.11	47	823
	Piney Woods	86	0.855	0.188	0.495	−287.2	1.10	53	584
	Post Oak Savannah	82	0.816	0.207	0.483	−219.7	1.13	45	726
	Rolling Plains	61	0.602	0.260	0.412	84.5	1.20	57	559
	South Texas Plains	45	0.449	0.261	0.351	53.2	1.20	18	314
Mean velocity (*V*-regressions)	All Regions	30	0.297	0.185	0.220	−2,494.6	1.09	372	4,629
	Blackland Prairie	3	0.029	0.185	0.188	−377.8	1.09	65	719
	Cross Timbers	23	0.221	0.159	0.180	−435.7	1.06	47	523
	Edwards Plateau	27	0.264	0.191	0.222	−175.5	1.10	40	381
	Gulf Prairies	48	0.474	0.150	0.206	−785.7	1.07	47	823
	Piney Woods	23	0.226	0.196	0.223	−237.8	1.11	53	584
	Post Oak Savannah	51	0.507	0.149	0.212	−701.0	1.07	45	726
	Rolling Plains	25	0.248	0.179	0.207	−329.3	1.09	57	559
	South Texas Plains	40	0.396	0.150	0.194	−292.3	1.07	18	314

Table 5. Regression coefficients, diagnostics, bias correction, and other information for regional regression equations as functions of watershed area, main-channel slope, and mean annual precipitation for estimation of four hydraulic properties of discharge measurements considered approximate to bankfull conditions in different ecoregions of Texas.—Continued

[NSE, Nash-Sutcliffe model efficiency coefficient; aRsq, adjusted coefficient of determination (adjusted R-squared); RSE, residual standard error in base-10 logarithmic units (log10) of respective response variable; VARsd, standard deviation of response variable; AIC, Akaike Information Criterion; Duan BC, Duan bias correction factor; Number of sites, number of U.S. Geological Survey streamgages; CDA, watershed area (contributing drainage area) based on square miles; MCS, dimensionless main-channel slope; MAP, mean annual precipitation based on inches per year; *A*, cross-section area, in square feet; *B*, water-surface top width, in feet; *Q*, discharge, in cubic feet per second; *V*, mean velocity, in feet per second. —, dimensionless; --, not applicable. The numeral “0” is truly zero for the Blackland Prairie based on regression approach to use ecological region as a categorical variable. Text in red is referenced directly in the report]

Regression coefficients											
Continuous variable coefficients				Categorical variable coefficients							
Intercept (log10)	CDA (log10)	MCS (log10)	MAP (log10)	Blackland Prairie (log10)	Cross Timbers (log10)	Edwards Plateau (log10)	Gulf Prairies (log10)	Piney Woods (log10)	Post Oak Savanna (log10)	Rolling Plains (log10)	South Texas Plains (log10)
0.8672	0.3958	0.0324	0.9232	0	−0.0695	−0.0833	0.0429	0.1415	0.1113	−0.0571	0.1819
0.2192	0.3695	−0.0733	1.1938	--	--	--	--	--	--	--	--
0.4939	0.4223	0.0589	1.1191	--	--	--	--	--	--	--	--
1.7085	0.4268	−0.0341	0.1162	--	--	--	--	--	--	--	--
1.5572	0.4323	0.2966	0.9894	--	--	--	--	--	--	--	--
1.7537	0.4037	−0.0502	0.3174	--	--	--	--	--	--	--	--
−0.7164	0.3682	0.2042	2.4015	--	--	--	--	--	--	--	--
0.4585	0.3810	0.1510	1.4495	--	--	--	--	--	--	--	--
7.3502	0.6331	0.3688	−3.3991	--	--	--	--	--	--	--	--
0.7879	0.2153	0.0117	0.6857	0	−0.0888	−0.0132	−0.0335	0.1666	0.0861	0.0434	0.2569
0.3419	0.2236	−0.0347	0.8736	--	--	--	--	--	--	--	--
0.3425	0.1781	−0.2668	0.4688	--	--	--	--	--	--	--	--
1.8015	0.3110	0.1880	0.1163	--	--	--	--	--	--	--	--
2.8354	0.2868	0.4693	0.2072	--	--	--	--	--	--	--	--
1.6270	0.1953	−0.0891	0.1375	--	--	--	--	--	--	--	--
−2.5598	0.0119	−0.0305	3.2070	--	--	--	--	--	--	--	--
0.4083	0.4297	0.5225	1.5806	--	--	--	--	--	--	--	--
8.9599	0.6025	0.4444	−4.9361	--	--	--	--	--	--	--	--
0.7806	0.5490	0.2658	1.4568	0	−0.0222	0.0132	−0.0084	−0.0500	0.0474	−0.0811	0.0582
1.2455	0.4136	−0.0299	0.8612	--	--	--	--	--	--	--	--
0.8572	0.6183	0.5194	1.7307	--	--	--	--	--	--	--	--
1.7879	0.6726	0.5596	1.0646	--	--	--	--	--	--	--	--
−0.0305	0.5524	0.2983	1.9986	--	--	--	--	--	--	--	--
1.6626	0.5935	0.2589	0.8213	--	--	--	--	--	--	--	--
0.8350	0.5383	0.1767	1.2939	--	--	--	--	--	--	--	--
1.0005	0.6193	0.4284	1.4277	--	--	--	--	--	--	--	--
6.3566	0.5730	0.5523	−1.9043	--	--	--	--	--	--	--	--
−0.0867	0.1535	0.2339	0.5342	0	0.0472	0.0963	−0.0511	−0.1913	−0.0640	−0.0240	−0.1238
1.0264	0.0442	0.0436	−0.3323	--	--	--	--	--	--	--	--
0.3610	0.1961	0.4610	0.6140	--	--	--	--	--	--	--	--
0.0809	0.2463	0.5949	0.9484	--	--	--	--	--	--	--	--
−1.5917	0.1202	0.0016	1.0113	--	--	--	--	--	--	--	--
−0.0815	0.1899	0.3100	0.4998	--	--	--	--	--	--	--	--
1.5531	0.1703	−0.0272	−1.1084	--	--	--	--	--	--	--	--
0.5426	0.2389	0.2779	−0.0227	--	--	--	--	--	--	--	--
−1.0051	−0.0602	0.1834	1.5030	--	--	--	--	--	--	--	--

The AIC is reported because it is a measure of the quality or information content of the regression for a given set of data and parameters. Other factors being the same, a lower AIC is indicative of a superior regression equation (Faraway, 2005, 2006). For example, the AIC of the *Q*-regression for the Cross Timbers ecoregion using only watershed area (AIC = 180, table 3) can be compared to the AIC of the *Q*-regression for the same ecoregion by using watershed area and mean annual precipitation (AIC = 158, table 4)—the reduction in the AIC value from 180 to 158 means that the equation using both watershed area and mean annual precipitation appears to be superior to the regression equation using only watershed area.

Regional regression equations for *A*, *B*, *Q*, and *V* were computed as functions of watershed area and mean annual precipitation by ecoregion, as well as by aggregating all the data by using ecoregion as a single categorical variable (the "All Regions" equations). The coefficients of the equations along with corresponding regression diagnostics, Duan bias correction, and other information are listed in table 4.

For the four equations that include watershed area, mean annual precipitation, and aggregated ecoregion (table 4), the variation explained by the regressions as measured by NSE are about 71 percent (cross-section area), 36 percent (top width), 76 percent (discharge), and 25 percent (mean velocity). In base-10 logarithmic transformation (log10), the RSEs of the regression equations are 0.252 log10 square feet (ft^2) for cross-section area, 0.319 log10 feet (ft) for top width, 0.247 log10 cubic feet per second (ft^3/s) for discharge, and 0.190 log10 feet per second (ft/s) for mean velocity, and the corresponding standard deviations of response are 0.465 log10 ft^2, 0.397 log10 ft, 0.507 log10 ft^3/s, and 0.220 log10 ft/s, respectively. The values for RSEs are less than those for VARsd, as anticipated, but show that percent changes uncertainty reduction of about −46 percent for cross-section area, about −20 percent for top width, about −51 percent for discharge, and about −14 percent for mean velocity. To clarify by example, the percent change from 0.465 to 0.252 for cross-section area is $100 \times (0.252 - 0.465)/0.465 = -46$.

Regional regression equations for *A*, *B*, *Q*, and *V* were first computed as functions of watershed area, main-channel slope, and mean annual precipitation by ecoregion. Next, ecoregions were aggregated into a single categorical variable by compiling the data from the eight ecoregions and recomputing the regression equations for *A*, *B*, *Q*, and *V* (the "All Regions" equations). The coefficients of the equations along with corresponding regression diagnostics, Duan bias correction, and other salient information are listed in table 5.

A review of the ecoregion-specific coefficients is informative. If the ecoregion-specific coefficients in table 5 are selected, the aggregate ("All Regions") *B*-regression has an intercept (conceptually, an offset on the real number line) of 0.7879, the categorical variable coefficient on the South Texas Plains ecoregion is 0.2569, and the categorical variable coefficient on the Cross Timbers ecoregion is −0.0888. A combined offset term for the *B*-regression for the South Texas Plains is thus 0.7879 + 0.2569 = 1.0448.

When the watershed properties are held constant in the South Texas Plains ecoregion, the values for *B*-regression variables for channels in this ecoregion are generally larger than the values for *B*-regression variables for any of the other ecoregions.

A combined offset term for the aggregate *B*-regression for the Cross Timbers ecoregion is 0.7879 − 0.0888 = 0.6991. Because −0.0888 is a negative quantity, values of *B* for channels in this ecoregion are generally smaller than for other ecoregions when watershed properties are held constant. The coefficient for the Blackland Prairie ecoregion is implicitly zero, so the offset using the aggregate *B*-regression for this ecoregion is 0.7879 + 0 = 0.7879, which is the reported regression intercept in table 5. Considering the absolute magnitude of ecoregion coefficients of less than about 0.05, values of *B* for channels in the Blackland Prairie ecoregion are generally between those for channels in the Edwards Plateau (−0.0132), Gulf Prairies (−0.0335), and Rolling Plains (0.0434) ecoregions.

Example computations with discussion help demonstrate how the equations listed in tables 3–5 might be used. The equations with the parameters of watershed area and mean annual precipitation were selected for the examples (figs. 7 and 8). As an aside, use of the aggregate region regressions using ecoregion as a categorical variable should be prioritized (fig. 7). Compared to the region-specific regressions (fig. 8), there is more information content within the aggregated regressions—sample sizes are larger, and the ecoregion serves to simply change the intercepts of the regressions.

Example computations of aggregate regional regression equations for the Cross Timbers ecoregion are provided in figure 7, and the *A*, *B*, *Q*, and *V* regressions are presented as functions of watershed area and mean annual precipitation by ecoregion category. Alternatively, example computations are provided for region-specific regression equations for the Cross Timbers ecoregion in figure 8, demonstrating how other estimates of *A*, *B*, *Q*, and *V* were obtained. This example watershed has similar estimates between the pairs of regression equations. For example, the discharge predicted by the aggregate ecoregion equation is 7,478 cubic feet per second (ft^3/s), whereas the discharge predicted by the Cross Timbers ecoregion-specific equation is 7,689 ft^3/s. Alternate predictions of discharge are possible when the aggregate regional regression equations (fig. 7) and region-specific regression equations (fig. 8) are applied to other ecoregions in Texas. Numerically similar predictions of discharge from the different regional regression equations (figs. 7 and 8) imply greater confidence in the general reliability of the predictions, but in general, numerically similar results should not be overinterpreted as ensuring that the predicted values are simultaneously accurate and precise, because considerable statistical uncertainty remains.

Statewide Regional Regression Equations and Potential Applicability in the High Plains and Trans Pecos Ecoregions

As explained in the section titled “Discharge Measurements Considered Approximate to Bankfull Conditions (the Subsetted Measurements),” the High Plains and Trans Pecos ecoregions have insufficient streamgaging data for analysis. After processing the discharge measurement data for these ecoregions, the only acceptable data were from 1 streamgage that provided 12 measurements in the High Plains ecoregion and 3 streamgages that provided a combined total of 10 measurements in the Trans Pecos ecoregion. Hence, insufficient data were available to develop ecoregion-specific regression equations for either the High Plains or Trans Pecos ecoregions.

It is difficult to judge which of the regression equations in tables 3–5 are appropriate for the High Plains and Trans Pecos ecoregions. It is suggested with considerable uncertainty, however, that the statewide equations (table 6) based on watershed area, main-channel slope, and mean annual precipitation could be used for the High Plains and Trans Pecos ecoregions. For example, the A-regression using these three predictor variables has an intercept of 0.377, a coefficient for watershed area of 0.384, a coefficient for main-channel slope of −0.055, and finally, a coefficient for mean annual precipitation of 1.112. This equation is based on 4,629 measurements obtained from the 372 streamgages. The preference for the equations possessing main-channel slope, which differs from the preference stated for the rest of the analyses reported herein, is based on a heuristic argument that the degrees of freedom are sufficiently large across the entire State to justify the use of three explanatory variables. Main-channel slopes in the High Plains ecoregion are minimal, given the flat terrain characterizing this vast region. Main-channel slopes in the arid basin and range physiography of the Trans Pecos ecoregion are generally larger and more variable than main-channel slopes in other parts of the State. Lastly, it is likely that statewide predictions from equations in table 6 would be more reliable in the High Plains ecoregion than in the Trans Pecos ecoregion because of the differences in main-channel slopes for the two ecoregions, with the slopes in the High Plains ecoregion being more similar to the main-channel slopes in the rest of the State.

The mean annual precipitation thus provides the key input variable for the High Plains ecoregion being different from the Gulf Prairies ecoregion. Precipitation is the key input variable because the High Plains has less than about one-half the rainfall than the Gulf Prairies with attendant differences in flow regimes when watershed area and main-channel slopes are otherwise held the same. A benefit of the statewide equations is that they possess a high level of statistical inference that comes with a substantial number of stations, or watersheds, and discharge measurements. Collectively, there should be sufficient degrees of freedom to achieve this high level of inference in regression coefficients (Helsel and Hirsch, 2002). The statewide equations might have other benefits elsewhere in the State, such as the ability to infer how predictions from tables 3–5 might compare to the statewide perspective obtained by using the equations listed in table 6.

Sand-Bedded Streams in Western Parts of the Rolling Plains Ecoregion

Detailed review of computations leading to the regression equations presented in tables 3–6 indicated a special type of stream with predominately highly mobile sand substrate in western parts of the Rolling Plains ecoregion warranted special attention. A total of 15 streamgages on sand-bedded stream channels were identified in the western part of the Rolling Plains ecoregion in northwestern Texas (fig. 1), but of these 15 streamgages, 07311790 and 08079575 lack measurements considered approximate to bankfull conditions. The 13 remaining streamgages are 07227500, 07228000, 07297910, 07298500, 07299540, 07300000, 07301300, 07307750, 07307800, 07308200, 07311800, 08079600, and 08080500. These 13 streamgages include 2 on the Canadian River in far northwestern Texas, 07227500 and 07228000, that were not used in the regression analyses. The sand-bedded channels of the streams at the 13 gaged locations of the streams in the western part of the Rolling Plains are generally shallow with small hydraulic depth (cross-section area divided by water-surface top width); stream channels in the Rolling Plains ecoregion characterized as sand bedded also tend to be shallower and wider than channels associated with other streamgages across the state. The relatively shallow and wide channels of the sand-bedded streams in the Rolling Plains ecoregion are formed by the transport of relatively large quantities of sand, as evidenced by the relative abundance of extensive, mobile sandbar complexes such as those shown in figure 9.

Stream-channel characteristics are gradational, and additional streams in the Rolling Plains ecoregion that were not characterized as sand bedded might transport relatively large quantities of sand compared to streams in other ecoregions, because their hydraulic properties are similar to the hydraulic properties of the sand-bedded streams. Part of the selection process for the 15 streamgages identified as being on sand-bedded streams included consideration of the operational practices of USGS staff working in the region, such as their discharge-records processing of frequently shifting stage-discharge relations in response to flood events. The channels at these streamgages are documented to regularly shift, or readjust, horizontally and vertically. These channels are also documented as forming, at times, nearly disconnected secondary and tertiary channels of flow across a common full channel, or primary floodway, transect. The hydraulic radius of the channel is often approximately equal to hydraulic depth at these streamgages.

Table 6. Statewide regression coefficients, diagnostics, bias correction, and other information for regional regression equations as functions of watershed area, main-channel slope, and mean annual precipitation for estimation of four hydraulic properties of discharge measurements considered approximate to bankfull conditions in Texas.

[NSE, Nash-Sutcliffe model efficiency coefficient; aRsq, adjusted coefficient of determination (adjusted R-squared); RSE, residual standard error in base-10 logarithmic units (log10) of respective response variable; VARsd, standard deviation of response variable; AIC, Akaike Information Criterion; Duan BC, Duan bias correction as described in text; Number of sites refers to the number of U.S. Geological Survey streamgages; CDA, watershed area (contributing drainage area) based on square miles; MCS, dimensionless main-channel slope; MAP, mean annual precipitation based on inches per year; *A*, cross-section area, in square feet; *B*, water-surface top width, in feet; *Q*, discharge, in cubic feet per second; *V*, mean velocity, in feet per second. —, dimensionless; --, not applicable. “Statewide” is a label indicating that ecological region was not used and is a parallel label to those used in tables 3–5. Text in red is referenced directly in the report]

Hydraulic (response) variable	Spatial perspective	NSE	aRsq	RSE	VARsd	AIC	Duan BC	Number of sites	Number of measurements	Regression coefficients: Continuous variable coefficients			
										Intercept	CDA	MCS	MAP
		(Percent)	(log10)	(log10)	(log10)	(—)	(—)			(log10)	(log10)	(log10)	(log10)
Area													
Cross-section area (*A*-regressions)	Statewide	60	0.597	0.295	0.465	1,842.4	1.26	372	4,629	2.231	0.400	--	--
Water-surface top width (*B*-regressions)	Statewide	26	0.264	0.341	0.397	3,173.0	1.42	372	4,629	1.827	0.211	--	--
Discharge (*Q*-regressions)	Statewide	70	0.695	0.280	0.507	1,360.4	1.22	372	4,629	2.478	0.471	--	--
Mean velocity (*V*-regressions)	Statewide	8	0.084	0.211	0.220	–1,281.0	1.12	372	4,629	0.247	0.071	--	--
Area and precipitation													
Cross-section area (*A*-regressions)	Statewide	68	0.681	0.262	0.465	757.7	1.21	372	4,629	0.366	0.401	--	1.193
Water-surface top width (*B*-regressions)	Statewide	30	0.300	0.332	0.397	2,938.8	1.39	372	4,629	0.778	0.228	--	0.671
Discharge (*Q*-regressions)	Statewide	75	0.751	0.253	0.507	415.8	1.20	372	4,629	0.814	0.472	--	1.064
Mean velocity (*V*-regressions)	Statewide	9	0.088	0.210	0.220	–1,300.9	1.12	372	4,629	0.446	0.071	--	–0.128
Area, slope, and precipitation													
Cross-section area (*A*-regressions)	Statewide	68	0.682	0.262	0.465	748.8	1.21	372	4,629	0.377	0.384	–0.055	1.112
Water-surface top width (*B*-regressions)	Statewide	30	0.301	0.332	0.397	2,934.4	1.38	372	4,629	0.788	0.211	–0.053	0.593
Discharge (*Q*-regressions)	Statewide	77	0.767	0.245	0.507	111.6	1.18	372	4,629	0.758	0.558	0.277	1.471
Mean velocity (*V*-regressions)	Statewide	21	0.210	0.196	0.220	–1,962.8	1.10	372	4,629	0.379	0.174	0.332	0.360

Figure 9. Examples of generally shallow, sand-bedded streams at U.S. Geological Survey streamgages *A*, 07307800; *B*, 07311800; *C*, 07311900; and *D*, 07308500 in the western part of the Rolling Plains ecoregion. Photographs by the U.S. Geological Survey.

Summary statistics of the watershed properties and the four hydraulic properties are listed in table 7 for 13 of the 15 streamgages on sand-bedded streams in the Rolling Plains ecoregion. A distinction is made that streamgages 07227500 and 07228000 are represented, but in the subsetting process described for regression equation development, these two streamgages were again removed and thus not included in either table 1 or 2. A multiple of main-channel slope (1,000 times main-channel slope) was reported in table 7 in the same manner it was reported in table 1.

Finally, these streamgages on sand-bedded streams are retained for, or included in, the Rolling Plains ecoregion-specific regression analyses discussed in this report. Exploratory regressions were made for the Rolling Plains ecoregion by using the sand-bedded stream classification as a categorical variable. The regressions used watershed area, main-channel slope, and mean annual precipitation as predictor variables. The p-value (statistical significance) of the sand-bedded classification was reviewed for each of the four regression equations, with one equation per hydraulic property. The exploratory results show that the sand-bedded classification might have statistical utility for some but not all of the four hydraulic properties. For cross-section area, the p-value was 0.45, indicating that the sand-bedded classification was not useful for estimating this hydraulic property. The p-value was <0.001 for water-surface top width with a positive regression coefficient, which is indicative of wider-than-typical channel sections as anticipated for streams classified as sand bedded. The p-value was <0.02 for discharge and <0.001 for mean velocity with a positive regression coefficient, which is indicative of faster-than-typical flow as anticipated by the preponderance of horizontal and vertical channel readjustments during flood events in sand-bedded streams. It is possible that water-surface top width and mean velocity are most sensitive to the sand-bedded classification, which makes sense because such streams are characteristically

Table 7. Summary statistics of four hydraulic and five watershed properties for 13 selected U.S. Geological Survey streamgages on sand-bedded rivers in western parts of the Rolling Plains ecoregion of Texas.

[Hydraulic properties of 199 discharge measurements consist of cross-section area, water-surface top width, discharge, and mean velocity. Watershed properties for the 13 selected streamgages consist of contributing drainage area, main-channel slope, mean annual precipitation, drainage density, and sinuosity ratio. The USGS station numbers of the 13 streamgages are 07227500, 07228000, 07297910, 07298500, 07299540, 07300000, 07301300, 07307750, 07307800, 07308200, 07311800, 08079600, and 08080500. This list includes the two streamgages on the Canadian River in far northwestern Texas (streamgages 07227500 and 07228000) that were not used in the regression analyses]

Hydraulic or watershed property	Units	Minimum	First quartile	Median	Arithmetic mean	Third quartile	Maximum
Cross-section area	Square feet	344	1,350	1,860	2,186	2,610	9,960
Water-surface top width	Feet	113	289	360	570	771	2,520
Discharge	Cubic feet per second	1,340	6,375	10,300	12,850	17,050	53,300
Mean velocity	Feet per second	1.21	3.94	5.56	5.95	8.18	11.30
Watershed area (contributing drainage area)	Square miles	244	930	1,581	3,822	2,929	18,180
1,000 times (main-channel slope)[1]	Dimensionless	0.847	1.434	1.807	1.982	2.682	3.394
Mean annual precipitation[2]	Inches	19.3	21.9	24.1	23.5	24.6	27.9
Drainage density	Miles per square mile	2.01	2.77	3.19	4.96	4.49	14.81
Sinuosity ratio	Dimensionless	1.30	1.40	1.54	1.60	1.66	2.20

[1]Multiplying the main-channel slope by 1,000 introduces an arbitrary constant offset that eliminates numerous leading zeros.

[2]For this analysis, the mean annual precipitation during 1981–2010 was used. Any authoritative source of mean annual precipitation for a suitably long period (perhaps 30 years) is sufficient.

wide and shallow and appear to be located close to upland parts of the western Rolling Plains. These watersheds appear to produce, on average, faster mean velocities within wider channels than is typical for more eastern watersheds in the Rolling Plains. However, detailed assessment of various scatterplots, residual plots, regression diagnostics, and degrees of freedom did not provide justification for creating additional regression equations with more variables for the Rolling Plains ecoregion than otherwise presented in this report.

Small Watersheds With Drainage Areas From 2 To 120 Square Miles

A detailed review of computations leading to the regression equations presented in tables 3–6 indicated complementary analyses specifically targeting relatively small watersheds could be useful. To improve the utility of the regression analysis of hydraulic properties for small watersheds (10–120 square miles [mi^2]), the dataset was further subsetted to include only those discharge measurements from watersheds having less than 120 mi^2 or smaller (hereinafter referred to as the “small watershed subset”). The watershed areas ranged from 2 to 119 mi^2 (inclusive) for the small watershed subset with 105 USGS streamgages. To enhance representation of bankfull conditions in these small watersheds, only those data representing a median annual return period of less than 1.5 to 2 years were retained, which reduced the dataset to 975 discharge measurements from 92 streamgages. The less than 1.5- to 2-year range of median annual peak discharges was computed by using a simple approach that also could accommodate censored peak values, defined as values less than or greater than a given cutoff value of discharge. The peak discharges for each streamgage through the 2014 water year were retrieved from the NWIS database (U.S. Geological Survey, 2015b, c). The period of record retrieved is streamgage-specific and difficult to succinctly summarize and further nuanced by “historical information” of peaks and not just systematic-record peaks; it is best stated that there were not beginning date criteria or a single begin-date criterion. Periods of record through the 2015 water year were retrieved. The following summary statistics are given for the water year value of the period of record of systematic peaks for the 424 streamgages: minimum 1898, first quartile 1966, median 1983, third quartile 1999, and maximum 2014.

The following computations were made for the data from each streamgage in the small watershed subset. First, individual discharge peaks were isolated by using the logic in Asquith and others (2019). Weibull plotting positions for the peak discharges then were assigned (Makkonen, 2005; Cohn and others, 2019). Next, a log-normal distribution was fit to the systematic peaks by using the R package survival, version 2.44-1.1 (Therneau and Grambsch, 2000; Therneau, 2015) with a Gaussian error distribution family. Because the regression is made in log space and the error distribution is Gaussian (normal), this has the effect of fitting a log-normal distribution to the data. The probabilities of interest are near the center of the distribution, and the use of zero curvature or zero skew in this analysis is appropriate.

The fitted log-normal distribution was used to estimate the relation between the base-10 logarithm of the peak discharge conditioned on censoring presence and the plotting positions by multiple-linear regression analysis. The intercept and slope of the regression analysis then were extracted and represent, respectively, the mean and standard deviation of the log-normal distribution. Once these two parameters of the distribution were available, the quantiles at the 0.333 probability (1 − [1 year/1.5 years]) and 0.500 probability (1 – [1 year/2 years]) were computed and retransformed to native units of cubic feet per second to form the site-specific 1.5- and 2-year peak discharges, respectively. The steps and processes outlined in the "Discharge Measurements Considered Approximate to Bankfull Conditions (the Subsetted Measurements)" section were repeated for the small watershed subset with the site specific 1.5- to 2-year peak discharges to develop a suite of small watershed regional regression equations (table 8). After evaluating the resulting regression equations by applying them to several small watersheds, it was determined that the equations should not be used on watersheds of less than 10 mi^2.

Regression Applicability, Limitations, and Implementation

Discharge measurements were extensively reviewed for this report by using many decision steps during the subsetting process to obtain the dataset used in regression analyses, but there are inherent limitations associated with these discharge measurements when they are used as response variables in regression. The locations of streamgages are biased towards stream cross sections that are conducive to unique stage-discharge relations (Turnipseed and Sauer, 2010). Discharge measurements are made with various types of instrumentation and reflect highly site-specific field conditions in time and place. Additional discussion of discharge measurements and their possible limitations for statistical study is provided in Asquith and others (2013, p. 1334–1336).

The quality control and quality assurance of individual measurement records had a relatively small effect on the data ultimately used compared to the relatively large effect of the selection process that was used to isolate those measurements considered approximate to bankfull conditions. The details are described in the section titled "Database of Sample Median and Standard Deviation of Observed Annual Peak Discharge." Bankfull conditions are conceptualized herein with great uncertainty and could be misinterpreted if not viewed in that perspective. For example, the Asquith and Roussel (2009) equations have residual standard errors on the order of one-third of a log-cycle and the mean of all (424 streamgages) standard deviations of the logarithms is about one-half of a log-cycle. The general uncertainty, in other words, involved just to determine those discharge magnitudes of interest is one-third to one-half log-cycle.

The considerations just described warrant consideration when the equations herein are used in order to avoid their potential misapplication; judgment of limitations and applicability is difficult, and only qualitative judgment appears possible. The remainder of this section generally considers limitations and applicability from a statistical perspective. Regression analysis for water-surface top width (B) appears to be the most challenging, perhaps because B is intrinsically represented by a single field measurement of channel width, whereas cross-section area (A) is computed from a substantial number of field measurements of the depth and width of flow recorded during a discharge measurement.

For watersheds having watershed area, main-channel slope, and mean annual precipitation values that are outside of the ranges listed in table 1, the applicability of the equations becomes particularly uncertain, and the potential for substantially larger error in estimation is expected. By necessity, the regression equations developed might not encompass all circumstances. For example, within a given ecoregion or even across the State, a sufficient number of streamgages monitoring certain combinations of watershed properties might not exist, or there might be an insufficient number of historical discharge measurements. The ranges of the predictor variables listed in tables 1 and 2 provide a rough check of equation applicability.

Additionally, the large number of regression equations for estimation of hydraulic properties in Texas makes the task of identifying optimal regression equations cumbersome. Thus, there is inherent difficulty in identifying the optimal regression equations for a given application. For example, if main-channel-slope data are missing, the end user has the option of using the regression equations that include watershed area and mean annual precipitation. An end user also has the information they need to make their own evaluations as to the relative effect of adding mean annual precipitation to a regression equation after watershed area has been added. For example, the end user could compare results from the watershed-area-only equations to those using watershed area and mean annual precipitation. An end user making computations for a stream location in the Post Oak Savannah ecoregion could likely use region-specific equations instead of the aggregate ecoregion equations, because this ecoregion encompasses a relatively large number of streamgages and measurements and has some of the more favorable regression diagnostics. Conversely, an end user making computations for a South Texas Plains stream location might favor the greater information content of the regression for the regions in aggregate because of the relatively small number of streamgages and measurements within this ecoregion. The decision process is, thus, complicated.

Table 8. Regression coefficients, diagnostics, bias correction, and other information for small watershed regional regression equations as functions of watershed area, main-channel slope, and mean annual precipitation for estimation of four hydraulic properties of discharge measurements at selected small watershed streamgages in Texas.

[NSE, Nash-Sutcliffe model efficiency coefficient; aRsq, adjusted coefficient of determination (adjusted R-squared); RSE, residual standard error in base-10 logarithmic units (log10) of respective response variable; VARsd, standard deviation of response variable; AIC, Akaike Information Criterion; Duan BC, Duan bias correction factor; Number of sites, number of U.S. Geological Survey streamgages; CDA, watershed area (contributing drainage area) based on square miles; MCS, dimensionless main-channel slope; MAP, mean annual precipitation based on inches per year; *A*, cross-section area, in square feet; *B*, water-surface top width, in feet; *Q*, discharge, in cubic feet per second; *V*, mean velocity, in feet per second. —, dimensionless; --, not applicable. The numeral "0" is truly zero for the Blackland Prairie based on regression approach to use ecoregion as a categorical variable]

Hydraulic (response) variable	Spatial perspective	NSE	aRsq	RSE	VARsd	AIC	Duan BC	Number of sites	Number of measurements
		(Percent)	(log10)	(log10)	(log10)	(—)	(—)		
Area									
Cross-section area (*A*-regressions)	All Regions	66	0.655	0.373	0.635	855	1.41	92	975
Water-surface top width (*B*-regressions)	All Regions	45	0.445	0.274	0.367	251	1.23	92	975
Discharge (*Q*-regressions)	All Regions	60	0.596	0.444	0.699	1195	1.69	92	975
Mean velocity (*V*-regressions)	All Regions	14	0.134	0.216	0.232	−214	1.13	92	975
Area and precipitation									
Cross-section area (*A*-regressions)	All Regions	68	0.680	0.360	0.635	783	1.37	92	975
Water-surface top width (*B*-regressions)	All Regions	46	0.450	0.272	0.367	242	1.23	92	975
Discharge (*Q*-regressions)	All Regions	63	0.627	0.427	0.699	1,117	1.62	92	975
Mean velocity (V-regressions)	All Regions	15	0.143	0.214	0.232	−224	1.13	92	975
Area, slope, and precipitation									
Cross-section area (*A*-regressions)	All Regions	69	0.684	0.357	0.635	770	1.37	92	975
Water-surface top width (*B*-regressions)	All Regions	46	0.451	0.272	0.367	242	1.23	92	975
Discharge (*Q*-regressions)	All Regions	63	0.627	0.427	0.699	1,119	1.62	92	975
Mean velocity (*V*-regressions)	All Regions	18	0.173	0.211	0.232	−258	1.12	92	975

Table 8. Regression coefficients, diagnostics, bias correction, and other information for small watershed regional regression equations as functions of watershed area, main-channel slope, and mean annual precipitation for estimation of four hydraulic properties of discharge measurements at selected small watershed streamgages in Texas.—Continued

[NSE, Nash-Sutcliffe model efficiency coefficient; aRsq, adjusted coefficient of determination (adjusted R-squared); RSE, residual standard error in base-10 logarithmic units (log10) of respective response variable; VARsd, standard deviation of response variable; AIC, Akaike Information Criterion; Duan BC, Duan bias correction factor; Number of sites, number of U.S. Geological Survey streamgages; CDA, watershed area (contributing drainage area) based on square miles; MCS, dimensionless main-channel slope; MAP, mean annual precipitation based on inches per year; *A*, cross-section area, in square feet; *B*, water-surface top width, in feet; *Q*, discharge, in cubic feet per second; *V*, mean velocity, in feet per second. —, dimensionless; --, not applicable. The numeral “0” is truly zero for the Blackland Prairie based on regression approach to use ecoregion as a categorical variable]

Regression coefficients											
Continuous variable coefficients				Categorical variable coefficients							
Intercept (log10)	CDA (log10)	MCS (log10)	MAP (log10)	Blackland Prairie (log10)	Cross Timbers (log10)	Edwards Plateau (log10)	Gulf Prairies (log10)	Piney Woods (log10)	Post Oak Savanna (log10)	Rolling Plains (log10)	South Texas Plains (log10)
Area											
1.991	0.456	--	--	0	−0.567	−0.894	0.052	0.055	0.105	−1.338	--
1.561	0.306	--	--	0	−0.361	−0.301	−0.031	0.060	0.358	−0.718	--
2.554	0.347	--	--	0	−0.540	−1.033	−0.049	−0.102	−0.032	−1.574	--
0.563	−0.109	--	--	0	0.027	−0.138	−0.101	−0.158	−0.137	−0.235	--
Area and precipitation											
−1.934	0.490	--	2.474	0	−0.520	−0.806	−0.207	−0.321	−0.010	−0.885	--
0.426	0.316	--	0.716	0	−0.348	−0.275	−0.106	−0.050	0.324	−0.587	--
−2.305	0.389	--	3.062	0	−0.482	−0.923	−0.370	−0.569	−0.175	−1.012	--
−0.370	−0.101	--	0.588	0	0.039	−0.117	−0.163	−0.247	−0.164	−0.128	--
Area, slope, and precipitation											
−1.484	0.370	−0.335	1.771	0	−0.483	−0.719	−0.314	−0.321	−0.035	−0.996	--
0.542	0.285	−0.087	0.534	0	−0.338	−0.253	−0.133	−0.049	0.318	−0.616	--
−2.261	0.377	−0.033	2.993	0	−0.478	−0.915	−0.381	−0.569	−0.177	−1.023	--
−0.775	0.007	0.302	1.220	0	0.005	−0.195	−0.067	−0.248	−0.142	−0.028	--

For general implementation, the aggregate regressions for *A*, *B*, *Q*, and *V* that are based on watershed area and mean annual precipitation as predictor variables (table 4) are suggested in preference to the others (tables 3 and 5). These preferences are demonstrated in figure 7 in contrast to the region-specific demonstration in figure 8. The suggestion is based on the fact that these equations ("All regions" listed in table 4) have the greatest information content to region-specific equations because the ecoregions have been treated as categorical variables, so that the number of streamgages and measurements involved is at a maximum. The end user of these equations is advised that the degrees of freedom might be insufficient to make reliable inferences on the importance of main-channel slope. Hence, no preference is expressed for these equations (table 5), even though they are presented herein. Main-channel slope is intrinsically involved, because it is codependent on watershed area and ecoregion. Having the distinct regional offsets in the aggregate equations may be beneficial by potentially assisting end users in site-specific interpretations where the applicability of a given ecoregion to a specific stream location is appropriate. Finally, for implementation to the smallest watersheds (few tens of square miles), it is suggested that the small watershed regression equations listed in table 8 would be preferred by many practitioners.

As a last detail about implementation, the Duan bias correction factor is suggested when predictions could be used for subsequent multiplicative operations for which preservation of a mean prediction as opposed to median prediction is favorable. Inspection of the Duan bias correction factor in tables 3–6 shows that these factors are all greater than unity, and as a result, application of the bias correction will systematically increase the magnitude of respective regression estimates. If an end user is satisfied with median predictions from the regional regression equations, then applying the Duan bias correction is not warranted.

Summary

The U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers, assessed statistical relations between hydraulic properties of streams at approximate bankfull conditions for different ecological regions (ecoregions) in Texas. Bankfull conditions were approximated by discharge measurements of a magnitude considered approximate to median annual peak discharge; selected measurements have a discharge that is within a range centered on estimates of median annual peak discharge from both regional regression equations and observational data.

Four hydraulic properties of streams were assessed for this report (cross-sectional area, water-surface top width, discharge, and mean velocity) by using linear regression methods. The regression equations resulting from this type of statistical assessment are at times referred to in the literature as "regional curves." Watershed properties of contributing drainage area, main-channel slope, mean annual precipitation, and ecoregion were used as predictor variables for the regression analyses.

For more than 125 years, USGS personnel in Texas have made direct measurements of discharge and observations of zero flow (that is, dry channel conditions) as part of the operational support of a statewide streamgage network. When first queried for this assessment on April 28, 2015, the USGS National Water Information System (NWIS) contained about 194,000 discharge measurements made in Texas. This total includes thousands of zero-flow values recorded for numerous stream locations, particularly in west Texas where the climate is arid to semiarid. USGS discharge measurements provide summaries of extensive field-collected data regardless of the techniques used to make the measurements, which have changed over time. In addition to the volume of flow per unit of time, individual discharge measurements generally contain field-collected supporting information (hydraulic properties), such as cross section area and water-surface top width.

Data from more than 103,000 records of measured discharge and ancillary hydraulic properties were assembled from summaries of discharge measurements for 424 USGS streamgages in Texas. This study demonstrates that the great number of records, wide range of flow conditions, and large number of streamgages contained within the USGS discharge measurement database in Texas facilitates the regionalization of discharge as well as mean velocity and other hydraulic properties.

Regionalization refers to a framework for statistical analyses that produces procedures for estimation of various properties, such as discharge, at ungaged or unmonitored locations from selected characteristics measured at both the ungaged locations and gaged locations. The statistical relations, expressed as regression equations, can be used to estimate basic hydraulic properties of channels from watershed properties (independent variables) for applicable watersheds and might be useful for engineering design purposes.

Summary statistics of the hydraulic and watershed were computed for 372 selected streamgages in Texas, and these 372 streamgages and their data constitute the subsetted measurements dataset described in this report. Eight of the 10 ecoregions in Texas are represented in the statewide summary statistics. The High Plains and Trans Pecos ecoregions are not represented for reasons described.

Ten ecoregions in Texas representing a combination of physiography, soils, bedrock geology, vegetation, and climate have been used to support studies in various scientific disciplines. The 10 ecoregions, listed in alphabetical order, are Blackland Prairie, Cross Timbers, Edwards Plateau, Gulf Prairies, High Plains, Piney Woods, Post Oak Savannah, Rolling Plains, South Texas Plains, and Trans Pecos. Ecoregions are used as cofactors in regression analyses represented as categorical variables.

Two sets of discharge measurements specific to the streamgages used in this report were aggregated. The first set is referred to as the "foundational measurements." The second set is referred to as the "subsetted measurements."

Discharge measurements and annual peak discharges from 424 streamgages in Texas were initially compiled. The 424 streamgages were selected in an ad hoc manner on the basis of availability of watershed properties; streamgage type; channel properties, such as non-concrete lined channels; and availability of direct measurements of discharge, such as non-theoretical weir computations. The measurements at these 424 streamgages constitute the foundational measurements.

Data from 372 of the 424 streamgages that provided the foundational measurements ultimately were used in the statistical relations described in this report. The dataset specific to the 372 streamgages is the aforementioned subsetted measurements. The reduction in streamgage count from 424 to 372 is attributable to the data screening procedures described.

Substantial preprocessing of these data, for quality control and assurance purposes, was necessary to produce the foundational measurements. These data were combined with watershed and climatology data. The foundational measurements consist of 103,158 records for the 424 streamgages.

Median annual peak discharge was estimated for each of the 424 streamgages by using a combination of regional regression equations in Texas previously developed for the 2- and 5-year annual peak discharges. The sample median of untransformed data and standard deviation of the base-10 logarithmically transformed (log10) annual peak discharge at each streamgage were computed. These peak discharge statistics were used in an algorithm used to subset the foundational measurements to those discharges considered approximate to median annual peak discharge, namely the subsetted measurements dataset. The subsetting process is delineated in a pseudocode language style.

Before the subsetted measurements dataset was used, additional preprocessing for enhancing quality control and assurance was made through a sequence of steps removing discharge records associated with highly questionable or conceptually implausible combinations of data values. For example, discharges computed to represent supercritical flow conditions were removed. Considerable visualization of combinations of the data was used. For example, records having exceptionally low mean velocities of less than 0.5 foot per second were removed. The final dataset consisting of 4,632 discharge measurements from the 372 streamgages for the subsetted measurements was used for the regression analyses.

Numerous regression equations were established herein to estimate the basic hydraulic properties of cross-section area (A), water-surface top width (B), discharge (Q), and mean velocity (V) as functions of selected watershed properties and ecoregion in Texas. Equations for these four hydraulic properties given unique sets of continuous-predictor variables represent an ensemble, meaning it is anticipated that A, B, Q, and V will be estimated together by end users for a given application.

For each hydraulic property, two separate types of regression analyses were made. First, separate regressions were computed for each of the eight ecoregions considered. Second, combined or aggregated regional regressions were made for which discharge measurement data from all 372 streamgages were used; these aggregated regional regression equations treat ecoregion as a categorical variable. Such treatment yields eight ecoregion-specific regression coefficients, given the eight ecoregions considered. Because logarithmic transformation exclusively was used for this assessment, a retransformation bias correction is appropriate in order to obtain an accurate estimate of a given hydraulic property and a simple retransformation bias correction known as the Duan bias correction. This bias correction is reported along with regression diagnostics such as Nash-Sutcliffe efficiency, adjusted R-squared, and residual standard error.

Regional regression equations for A, B, Q, and V were computed as functions of watershed area and ecoregion as well as by aggregating the data for the different ecoregions as a single categorical variable (the "All Regions" equations). Regression coefficients, bias correction along with regression diagnostics such as Nash-Sutcliffe efficiency, adjusted R-squared, and residual standard error and other information for regression as functions of watershed area, main-channel slope, and mean annual precipitation are presented in three separate tables. In total, nine regression equations (applicable to eight individual ecoregions and one aggregate of ecoregions) for each of the four hydraulic properties were developed for three distinct combinations of watershed properties as predictor variables; thus, 108 regression equations ($108 = 9 \times 4 \times 3$) result from this ecoregion-inclusive study. An additional 12 statewide regression equations are presented for combinations of predictor variables but explicitly lack ecoregion. Discussion of all 120 equations is presented with interpretation of selected diagnostics and example computations with discussion.

The High Plains and Trans Pecos ecoregions have insufficient streamgaging data for analysis. After processing the discharge measurement data for these ecoregions, the only acceptable data were from 1 streamgage that provided 12 measurements in the High Plains ecoregion and 3 streamgages that provided a combined total of 10 measurements in the Trans Pecos ecoregion. Hence, insufficient data were available to develop ecoregion-specific regression equations for either the High Plains or Trans Pecos ecoregions. It is suggested with considerable uncertainty, however, that the statewide equations based on watershed area, mean annual precipitation, and main-channel slope could be used for the High Plains and Trans Pecos ecoregions.

Detailed review of computations leading to the aforementioned regression equations indicates that a special type of stream with predominately highly mobile sand substrate in western parts of the Rolling Plains ecoregion might deserve special attention. A total of 15 streamgages on sand-bedded stream channels were identified in the western part of the Rolling Plains ecoregion in northwestern Texas, but of these 15 streamgages, two lack measurements considered approximate to bankfull conditions. The sand-bedded channels of the streams at the 13 gaged locations of the streams in the western part of the Rolling Plains are generally shallow with small hydraulic depth (cross-section area divided by water-surface top width); stream channels in the Rolling Plains ecoregion characterized as sand bedded also tend to be shallower and wider than channels associated with other streamgages across the state. Exploratory regressions were made for the Rolling Plains ecoregion by using the sand-bedded stream classification as a categorical variable. The exploratory results show that the sand-bedded classification might have statistical utility for some but not all of the four hydraulic properties. Detailed assessment of various scatterplots, residual plots, regression diagnostics, and degrees of freedom did not provide justification for creating additional regression equations with more variables for the Rolling Plains ecoregion than otherwise presented in this report.

To improve the utility of the regression analysis of hydraulic properties for small watersheds (10–120 square miles [mi^2]), the dataset was further subsetted to include only those discharge measurements from watersheds having less than 120 mi^2 or smaller. To better represent conditions in these small watersheds, only those data representing a median annual return period of less than 1.5 to 2 years were retained, which reduced the dataset to 975 discharge measurements from 92 streamgages. The steps and processes outlined in the "Discharge Measurements Considered Approximate to Bankfull Conditions (the Subsetted Measurements)" section were repeated for the small watershed subset with the site specific 1.5- to 2-year peak discharges to develop a suite of small watershed regional regression equations. After evaluating the resulting regression equations by applying them to several small watersheds it was determined that the equations should not be used on watersheds of less than 10 mi^2.

Discharge measurements were extensively reviewed for this report by using many decision steps during the subsetting process to obtain the dataset used in regression analyses, but there are inherent limitations associated with these discharge measurements when they are used as response variables in regression. The locations of streamgages are biased towards stream cross sections that are conducive to unique stage-discharge relations. Discharge measurements are made with various types of instrumentation and reflect highly site-specific field conditions in time and place. Various considerations of equation applicability and limitation of the equations are made. The considerations should be heeded when the equations herein are used in order to avoid their potential misapplication; judgment of limitations and applicability is difficult, and only qualitative judgment appears possible.

Regression analysis for water-surface top width (B) appears to be the most challenging, perhaps because B is intrinsically represented by a single field measurement of channel width, whereas cross-section area (A) is computed from a substantial number of field measurements of the depth and width of flow recorded during a discharge measurement.

For watersheds having watershed area, main-channel slope, and mean annual precipitation values that are outside of the ranges listed in this report, the applicability of the equations becomes particularly uncertain, and the potential for substantially larger error in estimation is expected. Additionally, the large number of regression equations for estimation of hydraulic properties in Texas makes the task of identifying optimal regression equations cumbersome.

For general implementation, the aggregate regressions for A, B, Q, and V that are based on watershed area and mean annual precipitation as predictor variables are suggested in preference to the others. The suggestion is based on the fact that these equations have the greatest information content to region-specific equations because the ecoregions have been treated as categorical variables, so that the number of streamgages and measurements involved is at a maximum. The end user of these equations is advised that the degrees of freedom might be insufficient to make reliable inferences on the importance of main-channel slope. Hence, no author preference is expressed for these equations (equations with main-channel slope).

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Publishing support provided by
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Asquith and others—**Regional Regression Equations for Estimation of Four Hydraulic Properties of Streams at Approximate Bankfull Conditions**—SIR 2020–5086

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20205086