Statistical Analysis to Describe the Complex Hydraulic Variability Inherent Channel Geometry

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Abstract

The effects of basin hydrology on channel hydraulic variability for incised streams were investigated using available field data sets and models of watershed hydrology and channel hydraulics for Yazoo River Basin, USA. The study presents the hydraulic relations of bankfull discharge, channel width, mean depth, cross-sectional area, longitudinal slope, unit stream power, and runoff production as a function of drainage area using simple linear regression. The hydraulic geometry relations were developed for sixty one streams, twenty of them are classified as channel evaluation model (CEM) Types IV and V and forty one of them are streams of CEM Types II and III. These relationships are invaluable to hydraulic and water resources engineers, hydrologists, and geomorphologists, involved in stream restoration and protection. These relations can be used to assist in field identification of bankfull stage and stream dimension in un-gauged watersheds as well as estimation of the comparative stability of a stream channel.

Keywords: Yazoo River Basin, incised streams, drainage area, hydraulic geometry, stochastic analysis.

List of symbols and abbreviations

a, *b*,	=	empirically-derived coefficients and exponents
A	=	cross-sectional area
d	=	flow depth (m)

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DA	=	drainage area (km^2)
g	=	gravitational acceleration
P-value	=	observed significance level of a statistical test
Q	=	flow rate (m^3/s)
Q/A	=	runoff production
S	=	channel slope, energy slope, bed slope
W	=	channel top width at the water surface
ρ	=	density of water
Ω	=	unit stream power

Abbreviations

CEM	=	Channel Evaluation Models
DEC	=	Demonstration Erosion Control
USACE	=	U.S. Army Corps of Engineers
USBR	=	U.S. Bureau of Reclamation

Introduction

In general, hydraulic geometry deals with variation in channel characteristics. Two types of hydraulic geometry analysis have been performed; at-a-station and downstream. Numerous researchers have used these methods to describe channel shape and form, to classify rivers, and to correlate channel geometry to geomorphologic variables.

Hydraulic geometry analysis of stream channels was first described by Leopold and Maddock (1953) to quantifying changes in hydraulic variables as a result of discharge changes. These variables are channel width, mean channel depth, and mean velocity. In general, cross-sectional area, channel depth, and mean velocity tend to increase significantly with changes in discharge. Hydraulic variables, such as cross-sectional area, channel width, mean channel depth, and mean velocity can be quantitatively related to discharge as a power function by use of simple linear regression. Datasets for determining these relations were obtained from discharge-measurement data that are collected as part of the operation of streamflow-gauging stations (Leopold, 1994).

Bankfull discharge is highly correlated with catchment area. It was shown that the flow discharge increases less rapidly than drainage area in many basins to give an exponent (n) value of less than 1 in the relation, $Q = a(DA)^n$ where Q is the flow discharge, DA is the drainage area, a and n are regression coefficients (Knighton, 1998).

Discharge is typically assumed to have a power-law relationship with drainage area in which the exponential coefficient is approximately 0.7 (Eaton et al., 2002). Compact basins have relatively higher peak discharges than elongated basins due to rapid accumulation of water in drainage area within compact watersheds. (Moussa, 2008). Conceptually, for a fixed channel gradient, incision rates are determined by peak discharges. Higher peak discharges raise transport capacities and competences (maximum particle size a river is capable of transporting), thus increasing the potential for incision (Whipple et al., 2000).

Rhoads (1991) considered downstream hydraulic geometry analysis as analysis of the bivariate relation between channel parameters (such as width and depth) and average or recurring discharge. The analysis is performed using data from numerous stream locations scattered along the channel. He showed that this relation does not uniquely define the form-discharge relation at any one site but rather describes the average spatial relation between hydraulic geometry and discharge. He also described at-a-station hydraulic geometry analysis as a treatment of flow geometry-discharge relations at a particular location over time. Therefore, these relations describe the correlation between flow geometry and an instantaneous discharge. In this study, he considered downstream hydraulic geometry using a depth-based approach.

Describing hydraulic properties of channel cross sections as a power function of flow depth was strongly supported by Garbrecht (1990) due to its simplicity and efficiency from the computational point of view. He cited that because hydraulic parameters such as cross-sectional area and hydraulic radius are a function of stage, the parameters require repeated evaluation during flow routing as stage varies with discharge. Therefore, smooth curves that describe the relationship between hydraulic parameters and stage expedite the computational procedure. He modified the simple power function to account for discontinuities at the overbank points by using a second power function having a translated coordinate system with the origin at the overbank elevation. Although his approach fits compound cross sections better, it is unnecessary in our present study since the simple power function describes the variation of cross-sectional area and hydraulic radius with depth in the incised portion of the channel extremely well.

Using three test sections on the Little Washita River of Oklahoma, Garbrecht (1990) tested the performance of the compound power function using standard error for quantification of the goodness of fit. For the simple power function, Garbrecht showed graphical fitting concluding that the traditional power function approach (such as the one used in this study) is effective where the channel sections are not compound and the hydraulic properties are not significantly affected by overbank flow.

Gates and Al-Zahrani (1996) focused on the uncertainty in unsteady open-channel flow modeling associated with quantifying model parameters. They concluded that most studies considering open-channel hydraulics in a stochastic setting have assumed simplifications such as low variance, statistical homogeneity, and independent normal probability distributions. To avoid these simplifying assumptions, they developed a model by defining the parameters in the Saint-Venant formulation as spatiotemporal random fields.

Ecclestone (1976) examined the relations between geometric properties (width, depth, width/depth ratio, cross-sectional area) of small streams and changes in discharge, geologic variables (particle size distribution of bed and bank materials) and slope. He achieved this examination through using correlation matrices and performed stepwise linear regression. He concluded that slope, coarse bed material, and fine bed material explained 90% of the variance within the inspected cross-sectional area.

Regional regression models of such relationships were developed by Dunne and Leopold (1978), and reproduced with minor changes by Rosgen (1998). These relations depict several generalized regions of the United States and are used to help researcher identify and confirm field indicators of bankfull stage.

Channel-forming discharges are often estimated in ungauged watersheds because surveys are difficult to conduct during high flows (Lee and Yen, 1997). Most studies consider peak discharges to be linearly related to drainage area (Leopold and Maddock, 1953; Kirkby, 1971; Brummer and Montgomery, 2003). As a result, basins with similar drainage areas are assumed to produce comparable discharges regardless of differences in basin morphometries and channel network geometries. This assumption is misleading given that runoff production is influenced by the distribution of drainage area with respect to length (Langbein, 1947).

In general, incision processes are modeled as the interaction between driving and resisting forces (Howard and Kerby, 1983). Incision rates are dependent on available energies, and thus, considered to be proportional to stream power, which is defined as: $\Omega = \rho g Q S$, where ρ is the density of water, g is gravitational acceleration, Q is discharge and S is reach gradient. Gravity, precipitation (streamflow), and uplift supply the energies needed to incise bedrock and they are commonly referred to as driving forces. In contrast, resisting forces include all phenomena associated with energy consumption or dissipation. Energy is required to transport sediment and is lost to turbulence created by sediment grains. Therefore, sediments are a resisting force, proportional to sediment sizes (caliber), quantities (load), and influxes (supply) (Sklar and Dietrich, 2003, 2008).

The United States Army Corps of Engineers (USACE, 1990) used the channel evolution sequence in developing regional stability curves correlating the bed slope of Type V reaches as a function of the measured drainage area. Quasiequilibrium, Type V reaches were determined by field reconnaissance of knowledgeable personnel. The regression exponent of the empirical relationship for Hickahala Creek, in northern Mississippi is -0.397 of the bed slope and drainage area.

The conceptual incised channel evolution model (CEM) has been of value in developing an understanding of watershed and channel dynamics, and describing the systematic response of a channel to a new state of dynamic equilibrium. In each reach of an idealized channel, Types I through V occur in series and, at a given location, will occur in the channel through time as shown in Figure 1. The depth width ratio increase along the stream.

1. Type II and III reaches are characterized by: a sediment transport capacity that is highly variable with respect to the sediment supply. Type III reaches are located downstream of Type II reaches and have a channel depth that is somewhat less than in Type II.

2. Type IV reaches are downstream of Type III reaches and are characterized by: a sediment supply that exceeds sediment transport capacity resulting in aggradation of the channel bed. Type IV reach is aggradational and has a reduced bank height. Bank failure has increased channel width. Type V reaches are located downstream of Type IV reaches and are characterized by: a dynamic balance between sediment transport capacity and sediment supply. For the effective discharge a width-depth ratio that exceeds the Type IV reach is found, and generally a compound channel is formed within a newly formed floodplain.

Methodology and Data Analysis

The Yazoo River Basin), one of the Mississippi's largest tributary basin and drains an area of about 34589.5 square kilometers. The basin covers all or parts of 30 counties and is about 321.9 kilometers in length and up to 160.9 kilometers in width in its northern half. Major streams include the Yazoo, Tallahatchie, Yalobusha, Coldwater, Bogue Phalia, Yocona, and Sunflower Rivers. Four major flood control reservoirs are also located in the basin; Arkabutla, Enid, Sardis, and Grenada as shown in Figure 2. The outlet for the basin is the Mississippi River at the confluence of the Yazoo River north of Vicksburg. Table 1 and 2 show streams data of Yazoo Basin that were used in the stability analysis.

Data from the Yazoo River Basin was used to develop a number of hydraulic geometry empirical equations for stable and incised stream. The dependent variables are annual mean discharge (m^3/s), top width (m), depth (m), longitudinal slope (m/m), shear stress, stream power, and runoff production. Each is a function of an independent variable; the drainage area (DA).

Dependent variables $= f(DA) = a(DA)^b$

Results

Power function relationships were developed using regression analyses for bankfull discharge, channel cross-sectional area, mean depth, and width as functions of watershed drainage area. The results of fitted power function and corresponding coefficients of determination for bankfull discharge, width, mean depth, cross sectional area, longitudinal slope, unit stream power, and runoff production for stable and incised channel are shown in Table (3) and Table (4), respectively. Figures 3 through 10 show the channel geometry relationships for the Yazoo River Basin for incised streams.

Results of this research show good fit of hydraulic geometry relationships in the Yazoo River Basin. The relations indicate that bankfull discharge, channel width, mean depth, cross-sectional area have stronger correlation to changes in drainage area than the longitudinal slope, unit stream power, and runoff production for streams CEM Types II and III. The hydraulic geometry relations show that runoff production, bankfull discharge, cross-sectional area, and unit stream power are much more responsive to changes in drainage area than are channel width, mean depth, and slope for streams of CEM Types IV and V. Also, the relations show that bankfull discharge and cross-sectional area are more responsive to changes in drainage area than are other hydraulic variables for streams of CEM Types II and III. The greater the regression slope, the more responsive to changes in drainage area will be.

In some hydraulic research the discrepancy ratio between (0.5-2) may be acceptable that is the ratio between measured and predicted value. This discrepancy ratio was considered an acceptable range for determining the accuracy of computed flow depth and flow width to observed measurements (Julien and Wargadalam, 1995).

It is found that the accuracy in predicting the hydraulic variables (flow discharge, channel width, depth, longitudinal slope, and cross sectional area) is more reasonable in the streams CEM Types II and III than the streams CEM Types IV and V. These relations are strong with coefficient of Determination (R^2) range from 0.73 to 0.83 for CEM Types II and III.

Discussion and Conclusions

Bankfull hydraulic geometry relationships are valuable to engineers, hydrologists, geomorphologists, and biologists involved in stream restoration and protection. They can be used to assist in field identification of bankfull stage and dimension in un-gauged watersheds. They do not, however, replace the need for field calibration and verification of bankfull stream channel dimensions.

The purpose of this paper is to present assistance in evaluating the stability of the channels. Bank failure, instability, and erosion rates are frequently used as measures of bank-stability classifications. This manuscript, characterizes in quantitative terms the manner in which discharge, width, depth, slope, cross sectional area, unit stream power and runoff production change with drainage area. Some hydraulic characteristics of streams in this study were measured quantitatively, it is found that these hydraulic variabilities were varying with drainage area as simple power function at a given river cross section. These characteristics are important determinants of the shape of the cross section of a channel and the progressive changes in its shape.

The summary of this study is shown in Tables 3 and 4. These show the exponents of power function for Type II and III are more than that for Type IV and Type V. The drainage area is more response to hydraulic geometry for

CEM type II and III than for Type IV and Type V. This means that the drainage area has more influence on hydraulic geometry at the beginning of the incised channel (deggradation stage) and its effect less through (aggradation stage.

The *P*-value was utilized to judge the significance of a variable used in the regression relationships. The *P*-value gives the probability of obtaining the test statistics, which must be less than the value of the significance level usually has a value of 0.05 or 0.10 (Freedman et al., 1997). The P-values in this study show very acceptable results and indicating statistical significance of the trend as shown in tables 3 and 4.

Natural streams adjust their hydraulic variability such as width, depth, and slope to maintain a balance between the water and sediment supplied from upstream, and that exported at downstream. However, in many basins, human activities have changed the balance between the water and sediment supply, resulting in potential changes to stream channels and their hydraulic geometry. The variability inherent in fluvial processes and sediment transport makes it complicated to evaluate the effects of these changes frankly, and even with extensive field measurements, there is always a reasonable chance of achieve results that are not conclusive.

The hydraulic geometry of the Yazoo basin streams was analyzed on the basis of available data of bankfull discharge, channel width, mean channel depth, longitudinal slope, drainage area, CEM Types IV and V and CEM Types II and III. Relations were established to quantify changes in geometry variables with changes in drainage area. The empirical relationships do not explicitly include the primary factors of water and sediment discharge, sediment load, hydraulic roughness, and channel morphology.

The width, mean depth, and mean velocity of water in a stream channel are typically power functions of discharge, producing three equations collectively referred to as hydraulic geometry. Theoretically, the exponents of these three equations are unit-sum constrained. Hydraulic geometry was determined to have less correlation with the proportional drainage area than with the flow discharge. Analyses of cross-sectional area, channel width, mean channel depth, and mean velocity in conjunction with changes in drainage area and annual mean discharge indicated that the channel width is much more responsive to changes in drainage area and annual mean discharge than are mean channel depth or mean velocity. Cross-sectional area, which combines the effects of channel width and mean channel depth, was also found to be highly responsive to changes in drainage area and annual mean discharge.

Analysis of the hydraulic variables by drainage area indicates that annual mean discharge is much more responsive than either mean channel depth or mean width. Cross-sectional area, which combines the effects of channel width and mean channel depth, was also found to be very sensitive to changes in drainage area. In comparing the hydraulic exponents that were developed from the hydraulic geometry analysis, it was found that the drainage area is strongly correlated with channel width, cross sectional area, longitudinal slope, unit stream power, and runoff production.

The application of these empirical relationships may be useful in preliminary design of stream rehabilitation strategies. In general, empirical relationships of bankfull width, depth, and cross-sectional area are the dependant variables but discharge is the independent variable rather than drainage area. Channel-forming (or bankfull) discharge is a more reliable independent variable for hydraulic geometry relations than drainage area. This is because the channel forming discharge is the driving force that creates the observed channel geometry, while drainage area is merely a surrogate for discharge. Discharge will vary depending on: geology, soils, vegetation, drainage area's shape, slope, drainage network, and land use. Channel shape, bed composition, and bank stability are probably controlling hydraulic geometry in these stream networks rather than drainage area.

All of the relationships presented here, including the hydraulic geometry relationships, are strictly empirical, i.e., the relationships describe observed physical correlations. As conditions and characteristics change from watershed to watershed, the relationships must be modified. Further work is necessary to develop additional data points to further explain the variability.

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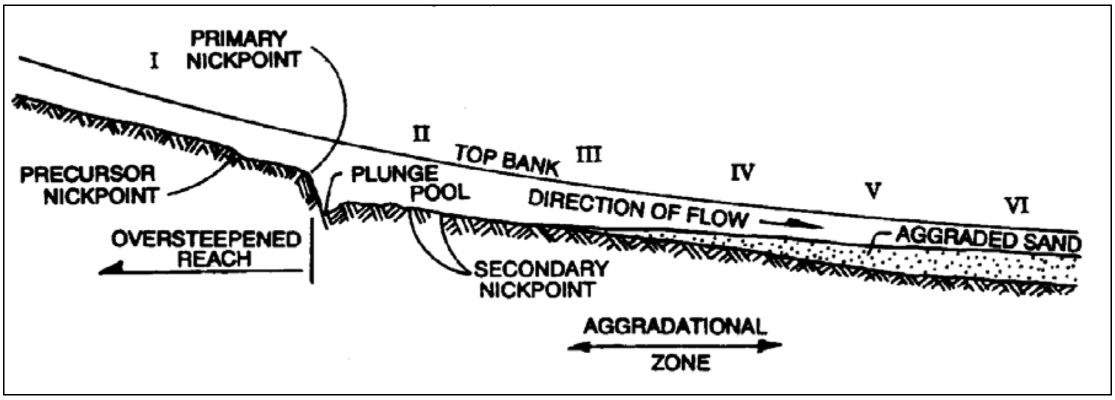

Figure 1: Incised Channel Evolution Sequence (after Schumm *et al*., 1984)

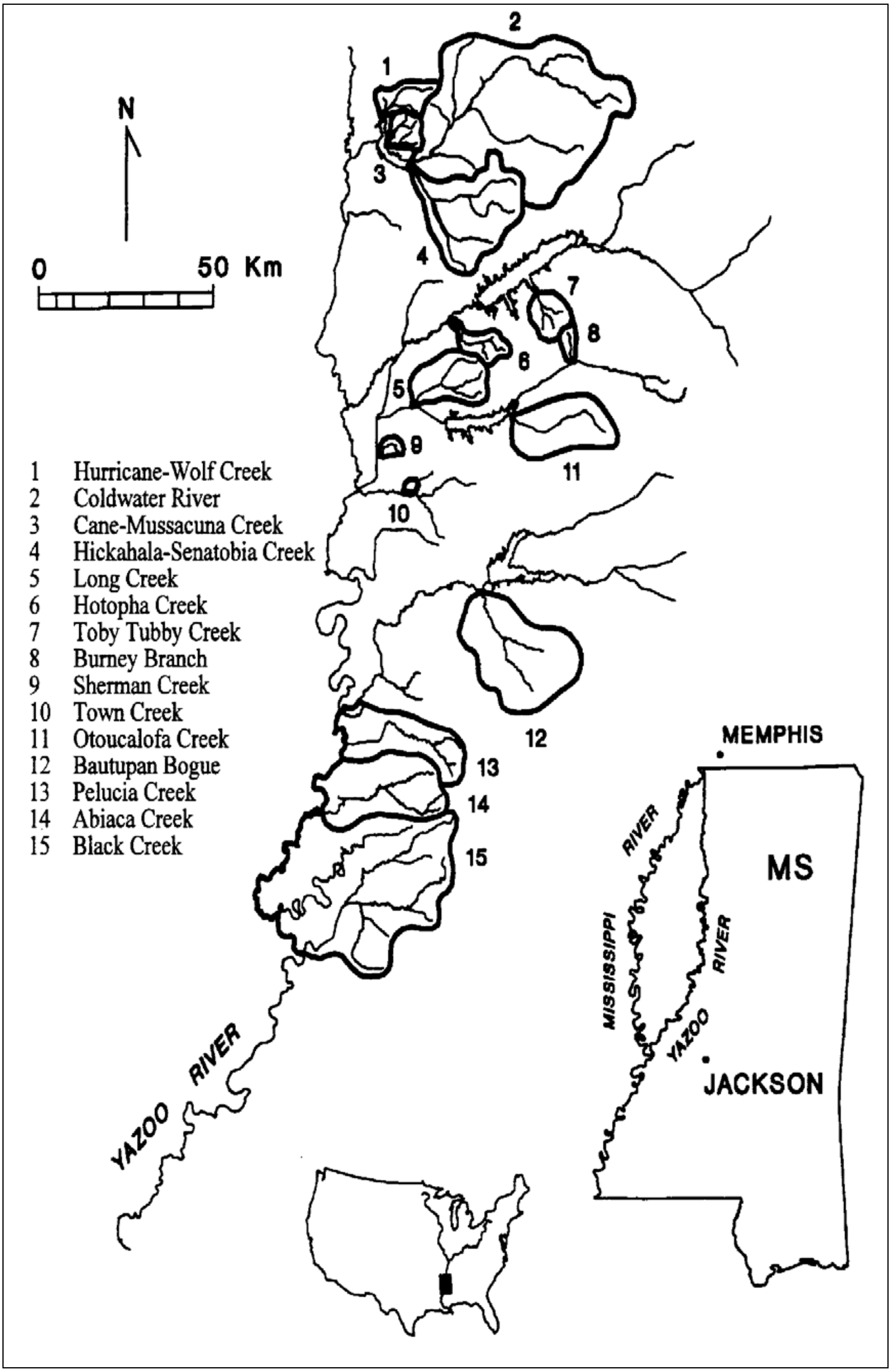

Figure 2: Site Location Yazoo River (USACE, 1990). Note that not all tributaries are shown.

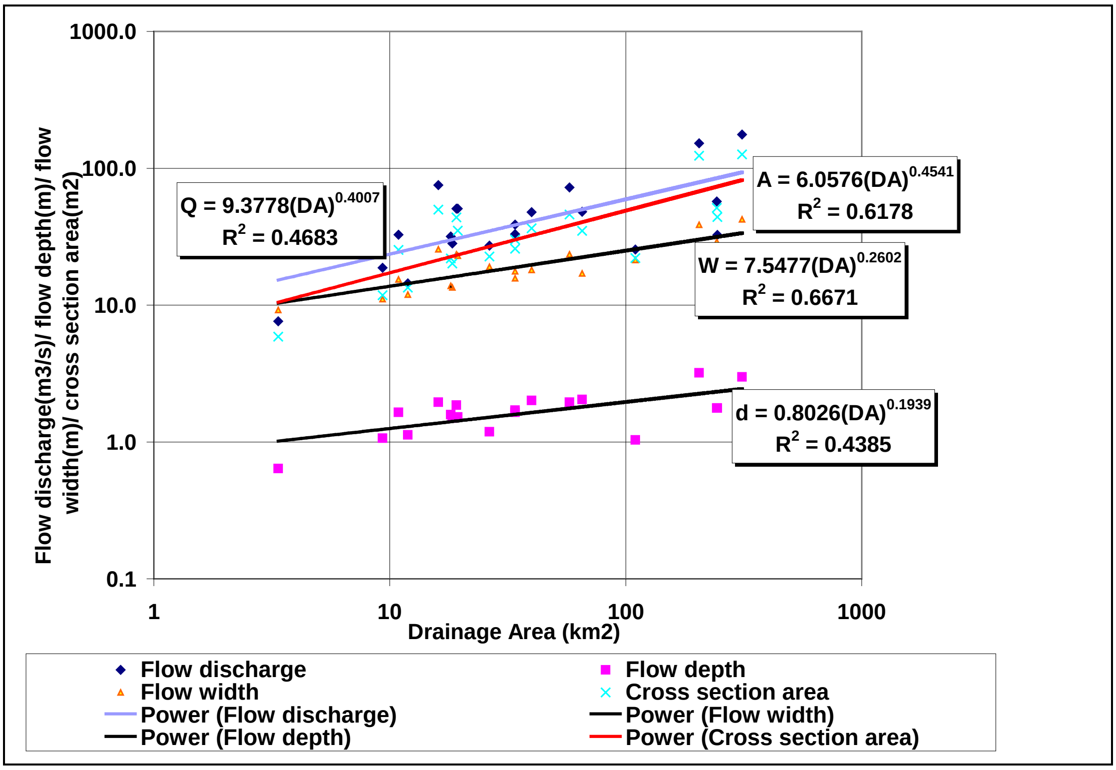

Figure 3: Channel geometry relationships for the Yazoo River Basin for the streams CEM Types IV and V

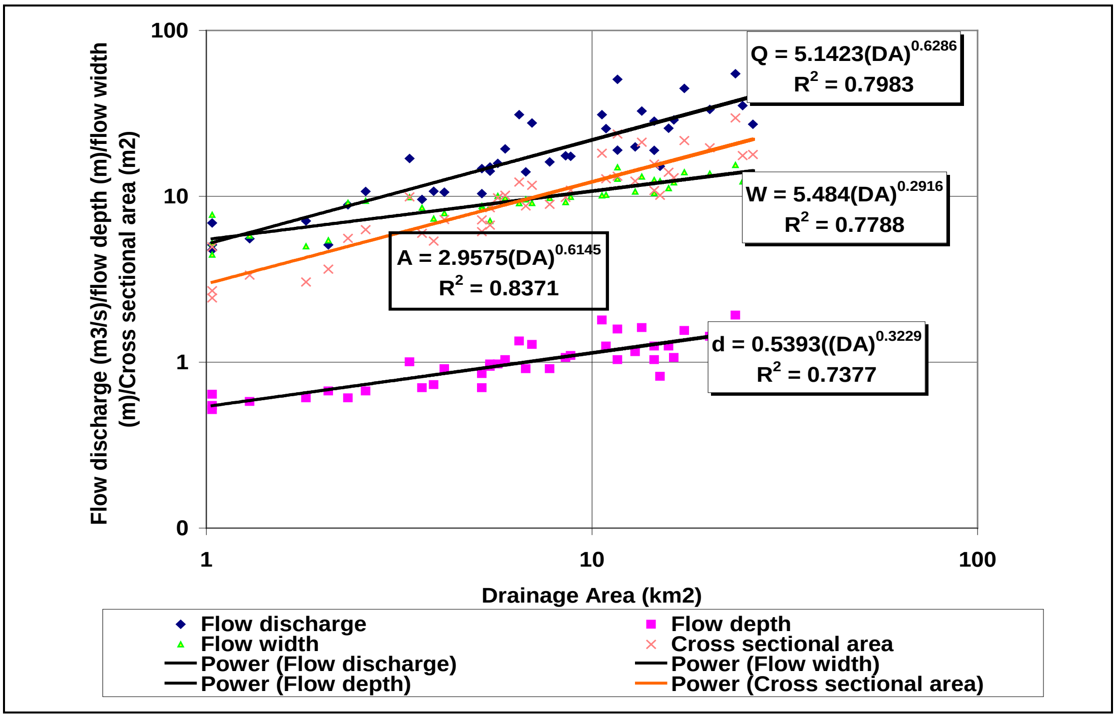

Figure 4: Channel geometry relationships for the Yazoo River Basin for the stream CEM Types II and III

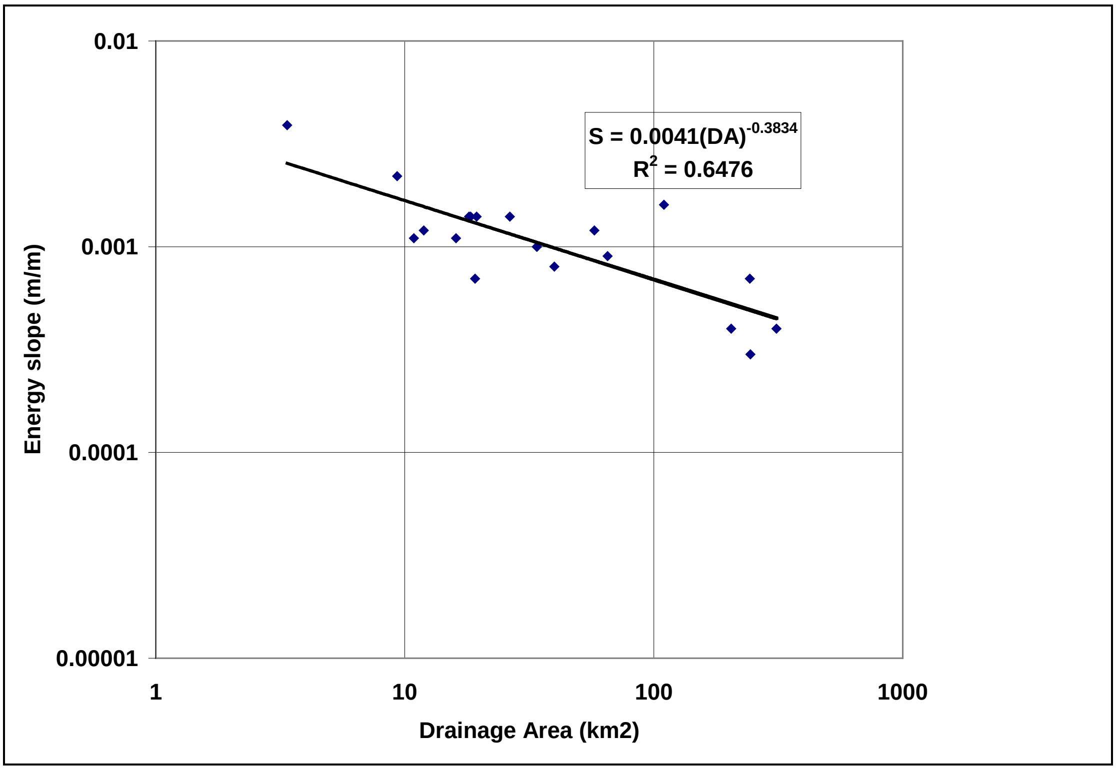

Figure 5: Channel longitudinal slope - drainage area relationship for the Yazoo River Basin for the streams CEM Types IV and V

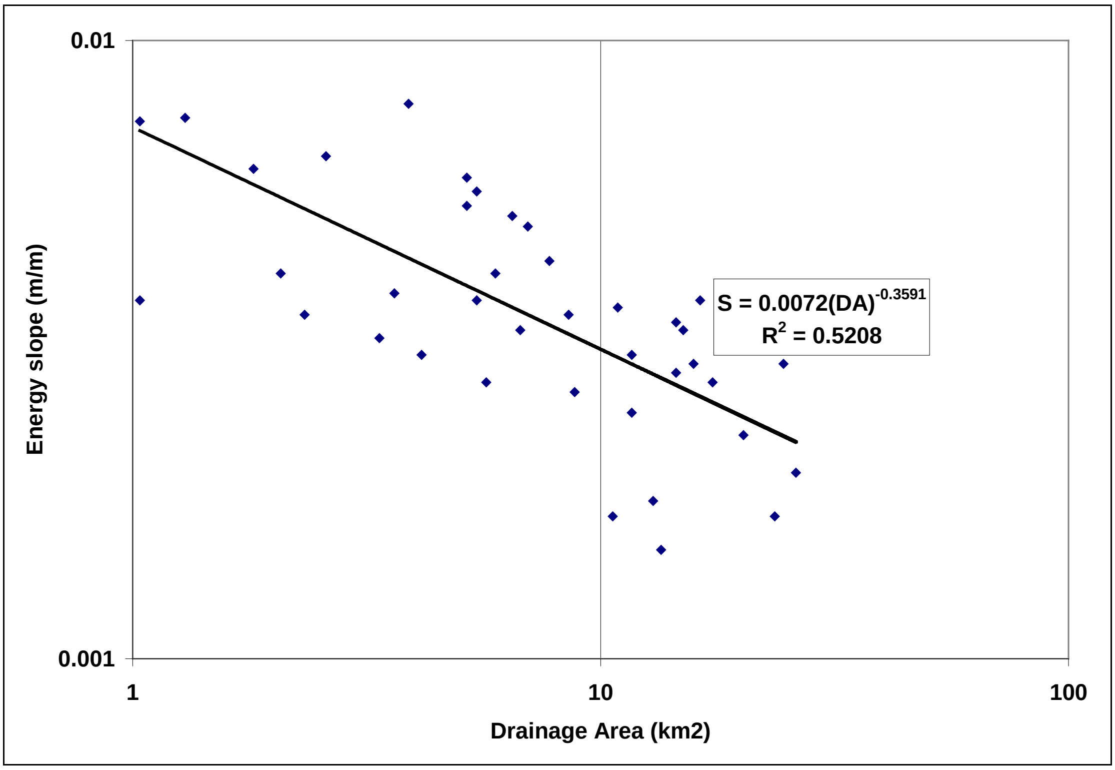

Figure 6: Channel longitudinal slope - drainage area relationship for the Yazoo River Basin for the stream CEM Types II and III

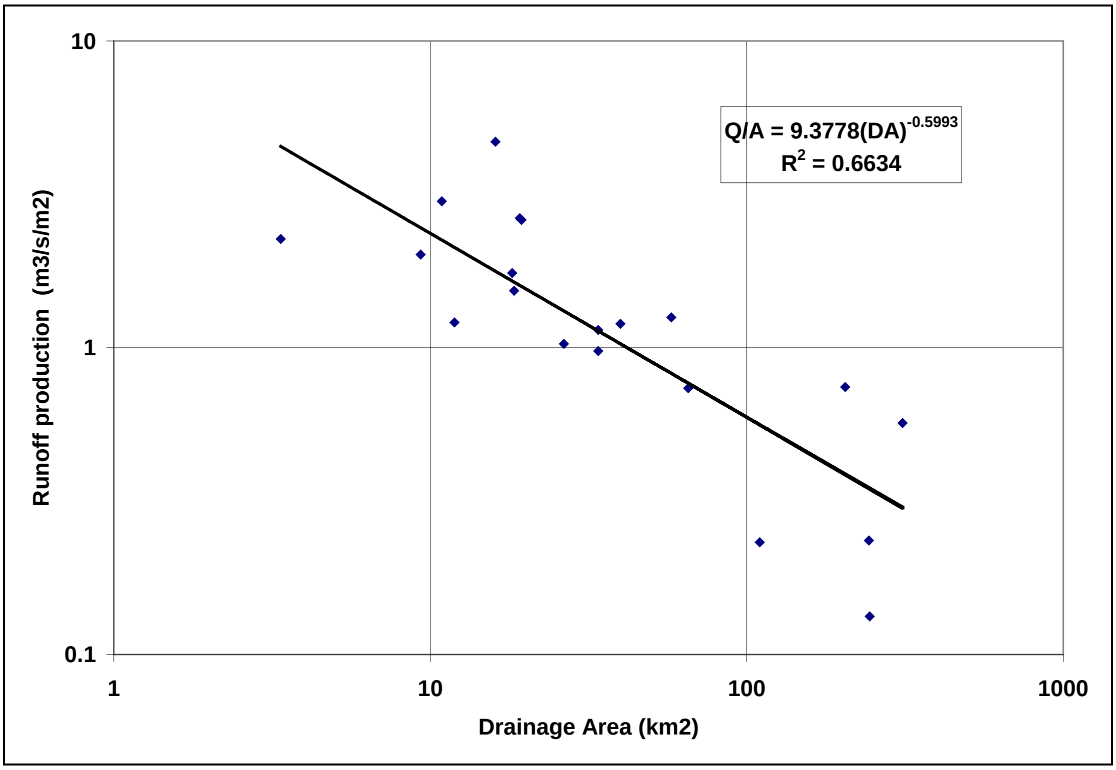

Figure 7: Runoff production - drainage area relationship for the Yazoo River Basin for the streams CEM Types IV and V

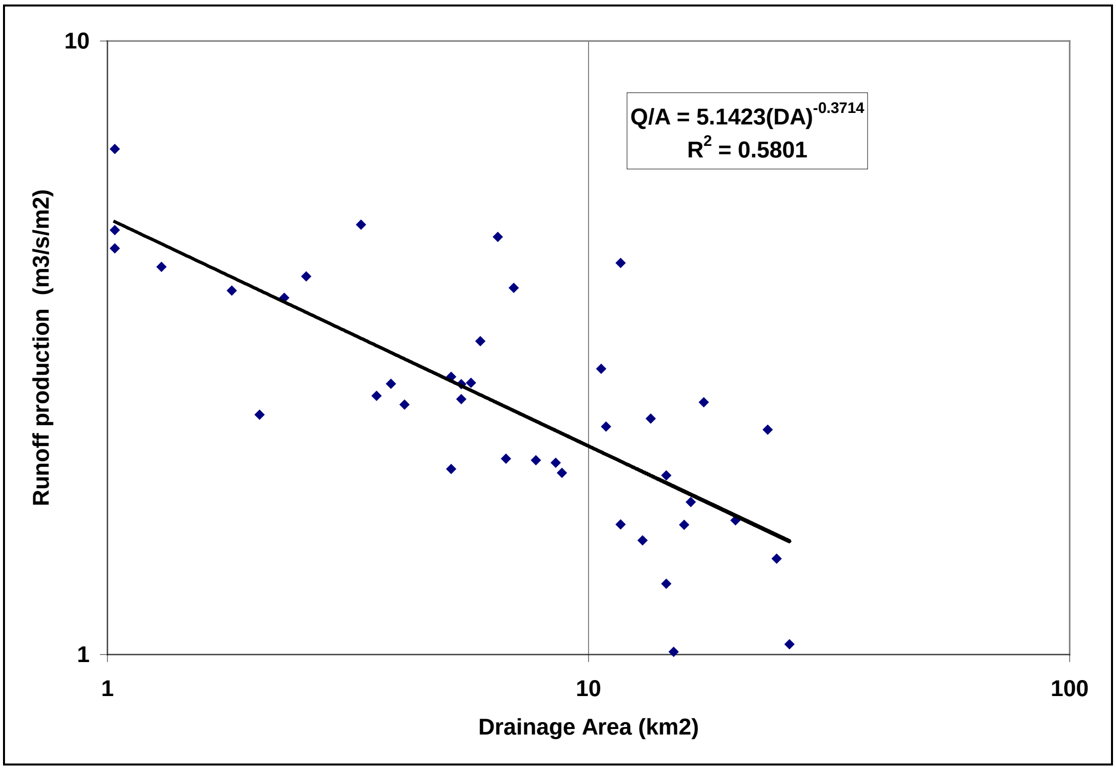

Figure 8: Runoff production - drainage area relationship for the Yazoo River Basin for the stream CEM Types II and III

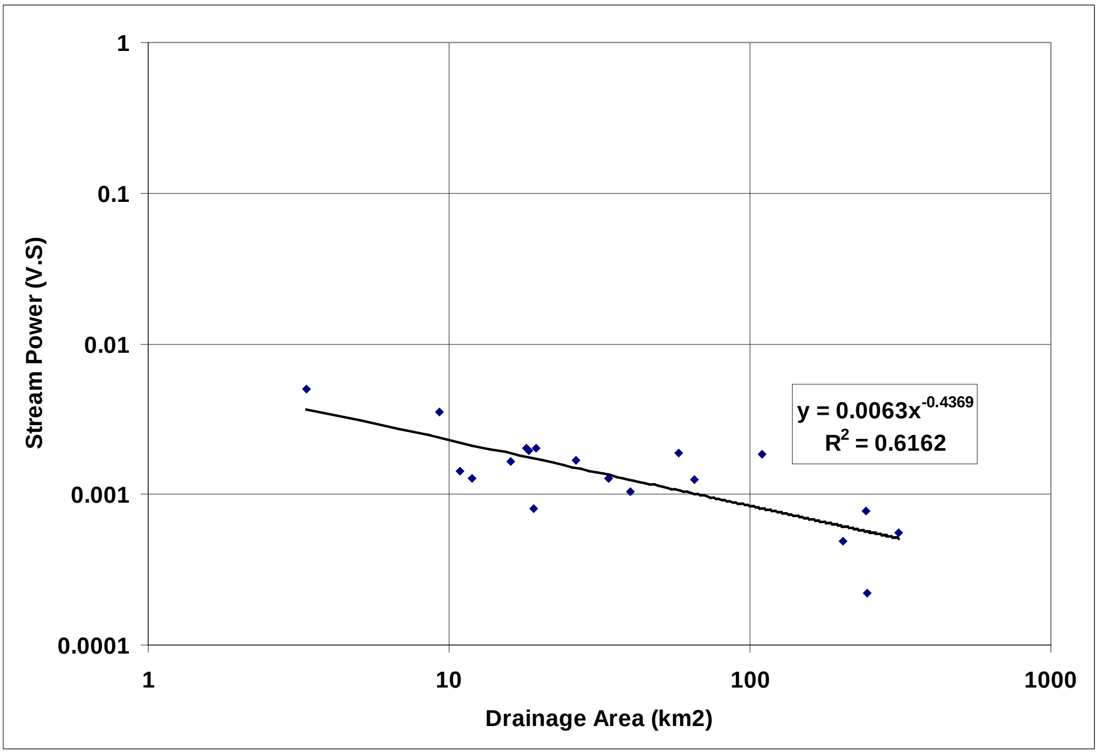

Figure 9: Unit stream power - drainage area relationship for the Yazoo River Basin for the streams CEM Types IV and V

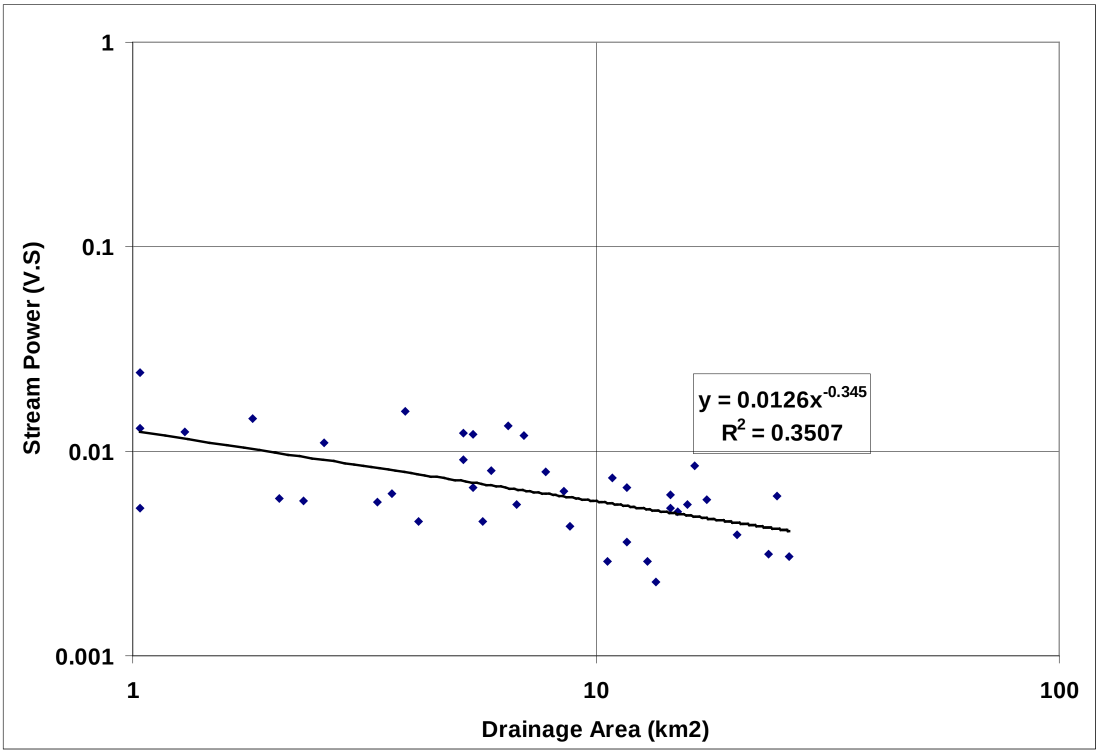

Figure 10: Unit stream power - drainage area relationship for the Yazoo River Basin for the stream CEM Types II and III

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Table.1: Yazoo Basin stable streams used in the stability analysis

Stream	$Q(m^3/s)$	Depth(m)	Width (m)	S	DA (km^2)
Abiaca 21	33	1.8	24.9	0.0003	244.
Abiaca 6	57	1.8	29.1	0.0007	243.
Long 2	27	1.2	19.1	0.0014	26.4
Burney 2	75	2.0	25.5	0.0011	16.1
Hurricane	48	2.0	18.1	0.0008	39.9
Meridian	8	0.6	9.2	0.0039	3.4
Miles	19	1.1	11.1	0.0022	9.3
Perry 2	51	1.9	23.5	0.0007	19.2
Abiaca 4	25	1.0	21.3	0.0016	109.
M. Worsham 3	33	1.6	15.4	0.0011	10.9
Abiaca 3	48	2.0	17.1	0.0009	65.3
Perry 1	51	1.5	23.0	0.0014	19.4
Splunge	14	1.1	11.9	0.0012	11.9
Yalobusha	17	3.0	42.3	0.0004	310.
Topashaw	15	3.2	38.6	0.0004	204.
Big	33	1.6	15.7	0.001	33.9
Big	39	1.7	17.7	0.001	33.9
Duncan	28	1.5	13.5	0.0014	18.4
Huffman	32	1.6	13.8	0.0014	18.1
Cane (Cook)	73	2.0	23.5	0.0012	57.8

Note: Streams are CEM Types IV and V

Table 2: Yazoo Basin incised streams used in the stability analysis

Stream	$Q(m^3/s)$	Depth(m)	Width (m)	S	DA (km^2)
M. Worsham 1	33	1.6	13.1	0.0015	13.5
Long 3	27	1.3	13.6	0.002	26.2
W. Worsham 1	31	1.8	10.1	0.0017	10.6
E. Worsham (2)	55	1.9	15.5	0.0017	23.6
Lick	45	1.6	14.0	0.0028	17.4
Perry 4	51	1.6	15.0	0.0031	11.7
Nolehoe 2	28	1.3	9.1	0.005	7.0
W. Worsham 4	31	1.3	9.1	0.0052	6.5
Johnson	20	1.2	10.7	0.0018	12.9
M-1	7	0.6	7.7	0.0038	1.0
MC4	9	0.6	9.1	0.0036	2.3
Meridian	19	1.0	12.8	0.0025	11.7
Johnson Creek Trib J-4	5	0.7	5.4	0.0042	2.1
Bear Creek B3	11	0.9	7.9	0.0031	4.1
Topashaw	15	0.8	12.3	0.0034	15.0
Anderson	10	0.7	8.5	0.0039	3.6
Twin	16	1.0	10.1	0.0028	5.7
Bear Creek B4	17	1.1	9.9	0.0027	8.8
Little Topashaw Creek	14	0.9	9.6	0.0034	6.7
Buck	33	1.4	13.7	0.0023	20.2
Topashaw Creek Trib T-	17	1.0	9.9	0.0033	3.4
Little Topashaw Creek	19	1.0	10.5	0.0035	14.5
Topashaw Creek Trib T-	10	0.7	8.7	0.0054	5.2
Hurricane 2	15	1.0	8.7	0.0038	5.4
Topashaw Creek Trib T-	28	1.2	12.5	0.0029	14.5
W-1	5	0.5	5.2	0.0074	1.0
Bear Creek Trib B2	18	1.1	9.2	0.0036	8.5
Hurricane	26	1.2	11.2	0.003	15.8
BC1	6	0.6	5.8	0.0075	1.3
Duncan	16	0.9	9.8	0.0044	7.8
Topashaw Creek Trib T-	11	0.7	9.4	0.0065	2.6
Topashaw Creek Trib T-	19	1.0	9.8	0.0042	6.0
Bear	35	1.4	12.3	0.003	24.6
Bear Creek Trib B-1	7	0.6	5.0	0.0062	1.8
Huffman	29	1.1	12.1	0.0038	16.3
Walnut	26	1.2	10.2	0.0037	10.9
Topashaw Creek Trib T-	15	0.9	8.4	0.006	5.2
Dry	14	0.9	7.1	0.0057	5.4
M-2	11	0.7	7.3	0.0079	3.9
Topashaw Creek Trib T-	5	0.5	4.5	0.0116	1.0

Note: Streams are CEM Types II and III

Table 3: Empirical coefficient for the streams CEM Types IV and V

Parameter	**Scaling Coefficient**	**Regression Exponent**	**Coefficient of Determination (R^2)**	**P- Statistic**
Q	9.3778	0.4007	0.4683	0.001246
W	7.5477	0.2602	0.6671	1.33E-05
d	0.8026	0.1939	0.4385	0.004127
A	6.0576	0.4541	0.6178	0.000108
S	0.004	-0.3834	0.6476	0.016609
Ω	0.0063	-0.4369	0.6162	0.011773
Q/A	9.3778	-0.5993	0.6636	0.004857

Table 4: Empirical coefficient for the stream CEM Types II and III

Parameter	**Scaling Coefficient**	**Regression Exponent**	**Coefficient of Determination**	**P- Statistic**
Q	5.1423	0.6286	0.7983	5.49E-09
W	5.484	0.2916	0.7788	6.14E-12
d	0.5393	0.3229	0.7377	1.92E-08
A	2.9575	0.6146	0.8371	2.88E-11
S	0.0072	-0.3591	0.5208	1.92E-05
Ω	0.0126	-0.345	0.3507	0.000485
Q/A	5.1423	-0.3714	0.5801	3.47E-06