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Original research

Variation in hydraulic geometry for stable versus incised streams in the Yazoo River basin – USA

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A B S T R A C T

The effects of basin hydrology on hydraulic geometry of channels variability for incised streams were investigated using available field data sets and models of watershed hydrology and channel hydraulics for the Yazoo River basin, USA. The study presents the hydraulic geometry relations of bankfull discharge, channel width, mean depth, cross-sectional area, longitudinal slope, unit stream power, and mean velocity at bankfull discharge as a function of drainage area using simple linear regression. The hydraulic geometry relations were developed for 61 streams, 20 of them are classified as channel evolution model (CEM) Types IV and V and 41 of them are CEM streams 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. A set of hydraulic geometry relations are presented in this study, these empirical relations describe physical correlations for stable and incised channels. Cross-sectional area, which combines the effects of channel width and mean channel depth, was found to be highly responsive to changes in drainage area and bankfull discharge. Analyses of cross-sectional area, channel width, mean channel depth, and mean velocity in conjunction with changes in drainage area and bankfull discharge indicated that the channel width is much more responsive to changes in both drainage area and bankfull discharge than are mean channel depth or mean velocity.

1. Introduction

In general, hydraulic geometry deals with variation in channel characteristics. Two types of hydraulic geometry analysis are typically 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 quantify 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 collected as part of the operation of streamflow-gauging stations (Leopold, 1994).

Rosgen (1994) presented a stream classification system that included: description of land use and vegetation in the basin, geology of the watershed, hydrology, channel bed and bank material, sediment concentration, channel pattern, and channel stability. He also added that planform and bed material character are combined into one code, improving the ease of use. Rosgen (1994) also included an entrenchment ratio, which is the ratio of the width of the flood-prone area to the surface width of the bankfull channel. Rosgen (1996) has also added a valley type classification.

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 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

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Nomenclature

a, b	empirically-derived coefficients and exponents
A	cross-sectional area at bankfull condition (m^2)
CEM	Channel Evolution Models
d	flow depth at bankfull condition (m)
DA	drainage area (km^2)
g	gravitational acceleration (m/s^2)
P-value	observed significance level of a statistical test
Q	flow rate at bankfull condition (m^3/s)
Q/A	mean velocity at bankfull discharge ($m^3/s/m^2$ or m/s)
S	channel longitudinal slope (m/m)
W	channel top width at the water surface at bankfull condition (m)
ρ	density of water (kg/m^3)
Ω	unit stream power (m/s or W/N)

accumulation of water in the 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 (i.e. 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 found 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 the 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 the usefulness of 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 de 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 did 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 researchers 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 & Yen, 1997). Most studies consider peak discharges to be linearly related to drainage area (Brummer & Montgomery, 2003; Kirkby, 1971; Leopold & Maddock, 1953). 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 & Kerby, 1983). Incision rates are dependent on available energy, and, thus, are 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 energy 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 caused by sediment grains. Therefore, sediments are a resisting force, proportional to sediment sizes, quantities (load), and influxes (supply) (Sklar & Dietrich, 2003, 2008).

The U.S. 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. Reaches in quasi-equilibrium, i.e, Type V reaches, were determined through field reconnaissance by 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 useful in developing an understanding of watershed and channel dynamics, and describing the systematic response of a channel to a new state of dynamic equilibrium (Watson et al., 1999). In each reach of an idealized channel, CEM Types I through V occur in series and, at a given location, will occur in the channel over time as shown in Fig. 1. The depth width ratio increase along the stream.

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