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Research papers

# Statistical filtering of river survey and streamflow data for improving At-A-Station hydraulic geometry relations

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ABSTRACT

Natural streams are characterized by variation in cross-section geometry, bed-slope, bed roughness, hydraulic slope, etc., along their channels resulting from several interacting features of the riverine system including the effects of discharge changes, geologic context, sediment load, etc. Quantitative and qualitative assessment of river flow dynamics requires sufficient knowledge of hydraulics and these geophysical variables. Average flow condition theory expressed as “At-A-Station” hydraulic geometry (AHG) relations are site-specific power-functions, relating the mean stream channel forms (i.e. water depth, top-width, flow velocity, and flow area) to discharge, have been studied since 50s. Establishing robust AHG relations requires pre-assessment of data quality by means of uncertainty analysis. Our paper introduces a recursive data filtering procedure to find both random and systematic errors in streamflow and river-survey data that can be used to produce robust and informative AHG relations. The method is first verified on synthetic data and then by experiments over: (1) real discharge-stage ratings provided by daily streamflow records of U.S. Geological Survey/National Water Information System dataset (USGS/NWIS), and (2) field river survey measurement data from USGS/NWIS. This produces robust AHG relations at 4472 monitoring stations across the U.S.

## 1. Introduction

Natural streams are characterized by cross-section geometry, bed-slope, bed roughness, etc. that varies along their reaches. The changes in shape and size of the river beds result from several interacting features of the riverine system including the effect of different flow regimes, sediment load, etc.

Quantitative and qualitative assessment of river flow dynamics, requires detailed knowledge of all the geometrical and geophysical variables that is normally collected via labor intensive field surveys (Turnipseed and Sauer, 2010), along with assessing the credibility and accuracy of streamflow measurement methods and measurands via statistical uncertainty analysis. Simplified hydraulic geometry relationships representing the average conditions over longer reaches could reduce the need for detailed field surveys and minimize the computational burden while carrying out numerical analyses of the flow dynamics.

Average conditions over natural river channels were first formulated as “regime-theory” hypotheses (Lacey, 1930, 1946) as a means for better interpretation of channel behavior. These regime theories followed the principle of the minimum energy dissipation rate which was generally developed for modeling stable channels (Langbein, 1964; Yang et al., 1981). The succeeding average flow condition theory expressed as “At-A-Station” hydraulic geometry (AHG) relations studied since the 50s (Leopold and Maddock, 1953; Leopold et al., 1964) are site-specific power-functions relating the mean stream channel forms (i.e. water depth, top-width, flow velocity, and flow area) to discharge.

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Validation of power-law hydraulic relations has also been attempted in multiple studies. Application of within bank-full flow records (generally below 1.5–2.33 year flood event) has been verified to support the validity of power-function relations (Dury, 1976; Garbrecht, 1990; Rhoads, 1991). Park (1977) and Richards (1973) disputed the AHG relations feasibility in outlining hydraulic geometry as the univariate relationship between depth and velocity against discharge as they are not directly involving the channel roughness as a key component.

AHG relationships for natural river channels traditionally derived from river channel surveys are practical tools for studying channel dynamics, deformation, and hydraulic design (Singh, 2003). Recent works (Dingman, 2007) demonstrated that power-function, as idealized riverbed geometry whose parameters are related to those of exponential relationship between mean water depth and top-width, are consistent with empirical AHG relations.

Establishing AHG relationships that have predictive skills for estimating riverbed geometry and its hydraulic properties without or with minimum river channel surveys (potentially from remote sensing) will require analysis of river-survey data for a wide range of rivers of various sizes with different flow regimes over diverse landscapes and regional features. All the recent studies of hydraulic geometry relations so far employed small to moderate sets of river surveyed data for either developing AHG or slope-area relations.

Leopold and Maddock (1953) established case studies on 20 and 10 river cross-sections in mid-west and southwest United States respectively and developed average power-law hydraulic geometry relations for those semi-arid regions. Park (1977) collected and assessed variations of power-law exponents of AHG relations derived from 139 stations reported in the literature.

Rhodes (1977) for the first time attempted to visualize exponents of AHG relations developed by 16 different sources using triangular coordinate (also known as Ternary diagram). He started from 332 AHG relations and ended to 315 sets since the exponents sum was equal or less than unit.

Rhodes (1977) examined 252 gaging sites in Missouri River basin and introduced a new approach to the analysis of downstream hydraulic geometry that focuses on variation in the coefficients and exponents in hydraulic geometry relations.

Dingman and Sharma (1997) developed a slope-area relationship via multivariate regression analyses for estimating discharge based on 621 flow hydraulics measurement captured from 128 stations in U.S. and New Zealand.

Bjerklie et al. (2003) explored the hydraulic data from 1012 measurements in 102 rivers in United States, New Zealand and four measurements at Amazon River in order to generate slope-area models from potentially observable river hydraulic variables via remote sensing tools for estimating discharge.

Harman et al. (2008) studied uncertainties and different types of potential errors in ‘Downstream’ hydraulic geometries computed from 1099 stations along the 114 rivers in southeast Australia.

Gleason and Smith (2014) based on a study on totally 88 monitoring stations along six rivers in the United States, investigated the interrelations of AHG coefficients and exponents of stations located on same river channel in the downstream direction.

Several studies attempted to develop physical and non-physical [or subjective versus analytical relations, described by (Hamilton, 2008)] functions for converting observed river stage-height (or other flow hydraulics) into river discharge. A single-valued rating curve (one-to-one discharge and stage-height relationship, where it is not significantly affected by unsteadiness and backwater effects) is common to be derived in the riverine flow. They can be fitted by applying graphical methods (Kennedy, 1984; Fenton and Keller, 2001) and statistical regression (Petersen- Øverleir, 2004; Moyeed and Clarke, 2005; Petersen-Øverleir, 2006).

The power-function of type:

$$H = c^{*}Q^{f} + H_0 \text{ or } Y_{max} = H - H_0 = c^{*}Q^{f} \tag{1 and 2}$$

is widely used in hydrometry as a regression model, where $H$ is stage-height, $Y_{max}$ is maximum water depth (the thalweg), $Q$ is discharge, and $c^{*}$, $f$, and $H_0$ (“cease-to-flow” water surface stage relative to an arbitrary datum where $Q$ is zero and stage datum is arbitrary) are calibration parameters (Fenton and Keller, 2001; Petersen-Øverleir, 2005; Pappenberger et al., 2006). The slope-area and power-law rating curve are widely used techniques, while their liability in discharge estimations also have been assessed in literature (Rantz, 1982; Dymond and Christian, 1982; Jarrett, 1984; Pappenberger et al., 2006). The AHG power-law relations are commonly applied as regression functions described by the following expressions:

$$W = aQ^{b};\ \bar{Y} = cQ^{f};\ \text{and } U = kQ^{m}, \tag{3, 4, and 5}$$

where the variables $Q$, $W$, $\bar{Y}$ and $U$ denote discharge, top-width, mean-depth, and mean flow velocity respectively. To satisfy flow continuity ($Q = W\bar{Y}U$), the sum of exponents ($b + f + m$) and the products of coefficient ($a \times c \times k$) must be equal to unity. The empirical AHG power-law relations can be theoretically explained by approximating river-bed geometry with similar power-law relationship:

$$\bar{Y} = \alpha W^{r};\ W = \left(\frac{\bar{Y}}{\alpha}\right)^{\frac{1}{r}} \tag{6 and 7}$$

and concerning the power-law form of bed geometry, it is inferred that

$$\bar{Y} = \frac{r}{r+1} Y_{max} \text{ or } \bar{Y} = \frac{r}{r+1}(H - H_0) \tag{8 and 9}$$

Chezy-Manning equation expressed as following:

$$U = \frac{u_m}{n}\bar{Y}^{p}S^{q} \tag{10}$$

while considering flow area as product of the mean depth, $\bar{Y}$ top-width, $W$, and energy-slope (or roughly bed-slope), $S$ thus discharge can be computed as

$$Q = U\bar{Y}W \text{ or } Q = \frac{u_m}{n}\bar{Y}^{p}S^{q}\bar{Y}W \tag{11 and 12}$$

in turn, $W$ and $\bar{Y}$ can be replaced by the recent equations associating them to the maximum depth (e.g. combining Eq. (7) with (8) which end up to relating $W$ to $Y_{max}$)

$$Q = \frac{u_m}{n}\left(\alpha^{\frac{1}{r}}\right)\left(\frac{r}{r+1}\right)^{p+1} S^{q}(Y_{max})^{\frac{r+rp+1}{r}} \tag{13}$$

where $n$ is Manning roughness coefficient, $p$ is the exponent of the hydraulic radius (which can be approximated by the mean depth, $\bar{Y}$ for wide channels), $q$ is the exponent of the energy slope (which is assumed to be equal to 0.5), and $u_m$ is Unit conversion factor (equal to 1 for SI unit, and $3.28^{1-p}$ for English unit). Hence, the general form of discharge-stage rating curve (Eq. (1)) can be extended as following form,

$$H = \left(\frac{n}{u_m}\right)^{\frac{r}{r+rp+1}}\left(\alpha^{\frac{1}{r+rp+1}}\right)\left(1 + \frac{1}{r}\right)^{\frac{r+rp}{r+rp+1}}(S)^{\frac{rq}{r+rp+1}}Q^{\frac{r}{r+rp+1}} + H_0 \tag{14}$$

According to Dingman, 2007, the α parameter is based upon $r$ shape exponent and bankfull width and depth of the river, and also AHG power-law relations (Eqs. (3)(5)) can be expressed likewise Eq. (11) highlighting the importance of reliable discharge-stage rating relation in estimating other AHG parameters.