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Research papers

Verifying the prevalence, properties, and congruent hydraulics of at-many-stations hydraulic geometry (AMHG) for rivers in the continental United States

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ABSTRACT

Hydraulic geometry (HG) has long enabled daily discharge estimates, flood risk monitoring, and water resource and habitat assessments, among other applications. At-many-stations HG (AMHG) is a newly discovered form of HG with an evolving understanding. AMHG holds that there are temporally and spatially invariant ('congruent') depth, width, velocity, and discharge values that are shared by all stations of a river. Furthermore, these river-wide congruent hydraulics have been shown to link at-a-station HG (AHG) in space, contrary to previous expectation of AHG as spatially unpredictable. To date, AMHG has only been thoroughly examined on six rivers, and its congruent hydraulics are not well understood. To address the limited understanding of AMHG, we calculated AMHG for 191 rivers in the United States using USGS field-measured data from over 1900 gauging stations. These rivers represent nearly all geologic and climatic settings found in the continental U.S. and allow for a robust assessment of AMHG across scales. Over 60% of rivers were found to have AMHG with strong explanatory power to predict AHG across space (defined as $r^2 > 0.6$, 118/191 rivers). We also found that derived congruent hydraulics bear little relation to their observed time-varying counterparts, and the strength of AMHG did not correlate with any available observed or congruent hydraulic parameters. We also found that AMHG is expressed at all fluvial scales in this study. Some statistically significant spatial clusters of rivers with strong and weak AMHG were identified, but further research is needed to identify why these clusters exist. Thus, this first widespread empirical investigation of AMHG leads us to conclude that AMHG is indeed a widely prevalent natural fluvial phenomenon, and we have identified linkages between known fluvial parameters and AMHG. Our work should give confidence to future researchers seeking to perform the necessary detailed hydraulic analysis of AMHG.

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1. Introduction

Rivers are essential for many human and ecosystem functions, and researchers have long been interested in the form and process of rivers. In particular, fluvial geomorphologists have used the concept of hydraulic geometry to understand the relationships between discharge and channel geometry for decades (Leopold and Maddock, 1953), enabling advances in many fields that aim to monitor and better understand rivers. Hydraulic geometry augmented development of rating curves already used by agencies throughout the world to relate river stage and discharge, and these resultant gauging stations have become essential for monitoring water resources and flood risks. This further understanding of hydraulic geometry has allowed agencies such as the United States Geological Survey (USGS) to provide daily discharge data for rivers throughout the US. In addition, hydrologic modeling also uses hydraulic geometry to calculate runoff routing times after large precipitation events and parametrize subgrid channels for streamflow simulation (e.g. Paik and Kumar, 2004; Neal et al., 2012), and hydraulic geometry has also been utilized to assess paleo flow conditions (Tinkler and Pengelly, 1995; Larson and Lamb, 2016). River restoration efforts also rely on hydraulic geometry as an easy-to-observe metric which can be related to other common fisheries management indices that are difficult to observe (Lamouroux and Souchon, 2002; Mosley, 1982; Rosenfeld et al., 2007).

The study of hydraulic geometry was launched by Leopold and Maddock in 1953 when they identified three power law equations that related discharge Q through a given station of a river with the flow width w, mean depth d, and mean velocity v of that station. They coined these equations (Eqs. (1)–(3)) as at-a-station hydraulic geometry (AHG).

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$$w = aQ^b \quad (1)$$

$$d = cQ^f \quad (2)$$

$$v = kQ^m \quad (3)$$

The coefficients (a, c, and k) and exponents (b, f, and m) are empirical parameters obtained by calibrating repeated field measurements of width, depth, and velocity with discharge in log-log space. AHG is only valid for in-bank flows, and out of bank flows exhibit distinct shifts in the rating curve that AHG power laws are unable to describe (Gleason, 2015). Similarly, Leopold and Maddock proposed downstream hydraulic geometry (DHG), which relates discharge with river width, depth, and velocity for stations along a river in the downstream direction for a given flow recurrence frequency. They found the relationship between these DHG parameters to take on the same power law form as AHG and used the same nomenclature as Eqs. (1)–(3) to describe DHG, though the coefficients and exponents in Eqs. (1)–(3) represent different fluvial properties between the two forms of hydraulic geometry.

Following Leopold and Maddock's, 1953 paper, AHG became an increasingly popular research topic. Many studies sought to verify the empirical relationships across a range of physiographic settings, while others aimed to discover the theoretical basis that explained the empirical observations. Through empirical analysis, Park (1977) and Rhodes (1977, 1978, 1987) separately found that AHG exponents are not similar among rivers in similar physiographic settings, leaving the question of what physical parameters determine the exponents of AHG unanswered. Despite objections made to the use of power law equations to describe the observed AHG relationships (Richards, 1973), a definitive theoretical explanation for AHG was provided by Ferguson (1986) through the derivation of AHG for different channel geometries using flow resistance equations. Attempts have been made to derive explicit formulations for the AHG coefficients and exponents, and Dingman (2007) showed that both the coefficients and exponents can be determined given a flow resistance equation and channel geometry *a priori*. Unlike the theoretical basis for AHG, no such definitive explanation has been found for DHG, resulting in the continued use of empirical data in order to identify factors affecting DHG (Gleason, 2015).

Calibrating the coefficients and exponents of the AHG and DHG equations requires data specific to discrete river stations, limiting the applicability of AHG and DHG to river stations for which these data have been gathered. This limitation, along with Ferguson's (1986) work, led to the conclusion that AHG is fundamentally site-specific and unrelated through space (Phillips, 1990). Dingman (2007) found that coefficients and exponents are related, but his first-principles analysis holds only at a single station. Gleason and Smith (2014), however, discovered a spatial relationship between the AHG coefficients and exponents they termed at-many-stations hydraulic geometry (AMHG). This finding seemingly contradicts the assumption that these parameters are spatially independent and site specific, and states that the AHG coefficient may be determined from the AHG exponent, and vice versa. Thus, Dingman's, 2007 important at-a-station conclusions cannot predict why multiple stations should have a spatially predictable variation in coefficients and exponents. AMHG was first introduced as a log-linear relationship between a river's AHG coefficients and exponents (a and b, c and f, k and m), effectively halving the number of unknown AHG parameters from six to three if AMHG were known (Gleason and Smith, 2014). Gleason and Wang (2015) advanced the understanding of AMHG when they showed that multiple AHG curves representing different stations on the same river reliably converge to congruent hydraulic quantities when plotted on the same axes (coined congruent discharge Q_c, width w_c, depth d_c, and velocity v_c), and they argued that AMHG exists as a consequence of this convergence, further confirmed by Shen et al. (2016). Gleason and Wang argued that the values of the congruent hydraulics are represented by the spatial mode of the time mean for each of these station values and as a result concluded that the strength (r^2) of AMHG was a geomorphic index indicating the degree of convergence of AHG curves. Shen et al. (2016) built upon this work and stated that the 'similar time mean' condition was a sufficient but not necessary condition for AMHG, leaving open the question of whether or not AMHG is a mathematical construct or geomorphic phenomenon. Finally, Gleason and Wang proposed p_{int} as a topological index indicating the percentage of rating curves intersecting within the range of observed hydraulic quantities. They argued that this can indicate the strength of AMHG *a priori*, but this hypothesis has never been tested on a wide range of rivers.

AMHG's most prominent application to date has been in remote sensing of river discharge (Bonnema et al., 2016; Durand et al., 2016; Gleason and Smith, 2014; Gleason et al., 2014). Despite a lack of understanding regarding the physical meaning of AMHG, and in particular the meaning of the congruent discharge, AMHG's importance has been demonstrated through its influence on reliable discharge estimation. It has been shown that the success of the AMHG discharge estimation algorithm strongly relates to whether the congruent discharge is within the range of a river's observed discharge (Gleason and Wang, 2015), though the likelihood of this occurrence is unknown.

These latest developments push AMHG toward maturity, but large-scale testing of the ideas discussed above has not been performed. Although hydraulic congruence has been shown to exist in theory and from limited datasets, the physical hydraulic quantities represented by congruent hydraulics are not currently understood, and little research has focused on uncovering their meaning. Furthermore, to date, the full width, depth, and velocity AMHG has been robustly examined on only six rivers (Gleason and Smith, 2014). AMHG has also been demonstrated on 57 other rivers by Shen et al. (2016) using USGS gauge data, though these data were employed without a rigorous verification of the phenomenon. Additionally, fluvial geomorphic or climatic factors that influence the formation of AMHG remain poorly understood, and possible spatial patterns in AMHG have not been identified.

To these ends, we here compile the largest dataset ever used to test the full suite of width, depth, and velocity AMHG in order to address unanswered questions regarding the driving factors of AMHG. We first calculate AMHG for 191 rivers and then analyze spatial patterns and geomorphic/climatic controls in these data. Our work thus parallels that of earlier hydraulic geometry researchers seeking to understand AHG across spatial and climactic scales (e.g. Park, 1977; Richards, 1973; Rhodes, 1977, 1978, 1987). We then assess previous assumptions/conclusions about AMHG, including the relation of congruent hydraulics to observed hydraulics, and, critically, whether or not the full suite of AMHG is observed beyond the six rivers for which it has been previously demonstrated. The paper concludes with discussion of the implications of our findings on the application of AMHG to a wide range of fluvial problems.

2. Methods

We relied on field-measured quantities of width, velocity, and discharge provided by the USGS to assess AMHG. The USGS maintains numerous gauging stations across the US, and each one of these requires periodic measurements to assess shifts in the rating curve due to sediment scour/deposition or other changes to channel geometry. These data are provided free to the public by the USGS, and two forms of data are available: the stage recorded by

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