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Reenvisioning cross-sectional at-a-station hydraulic geometry as spatially explicit hydraulic topography

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ABSTRACT

Transect-based hydraulic geometry is well established but depends on a complex set of subjective fieldwork and computational decisions that sometimes go unexplained. As a result, it is ripe for reenvisioning in the light of the emergence of meter-scale, spatially explicit data and algorithmic geospatial analysis. This study developed and evaluated a new spatially explicit method for analyzing discharge-dependent hydraulics coined 'hydraulic topography' that not only increases accuracy but also eliminates several sample- and assumption-based inconsistencies. Using data and hydrodynamic simulations from the regulated, gravel–cobble-bed lower Yuba River in California, power functions were fitted to discharge-dependent average width, depth, and depth-weighted velocity for three spatial scales and then their corresponding exponents and coefficients were compared across scales and against ones computed using traditional approaches. Average hydraulic values from cross sections at the segment scale spanned up to 1.5 orders of magnitude for a given discharge. Transect-determined exponents for reach-scale depth and velocity relations were consistently over- and underestimated, respectively, relative to the hydraulic topography benchmark. Overall, 73% of cross-sectional power regression parameters assessed fell between 10 and 50 absolute percent error with respect to the spatially explicit hydraulic topography baseline. Although traditional transect-based sampling may be viable for certain uses, percent errors of this magnitude could compromise engineering applications in river management and training works.

1. Introduction

The use of hydraulic geometry (HG) relations is widespread in river science and restoration. At-a-station HG relationships have been applied in geomorphic process assessment (Knighton, 1975; Merigliano, 1997; Pasternack, 2011), river restoration (Copeland et al., 2001; Shields et al., 2003), stream classification (Leopold and Wolman, 1957; Rosgen, 1994), waterfall systematics (Wyrick and Pasternack, 2008), aquatic ecosystem evaluation (Hogan and Church, 1989; Jowett, 1998), and estimating river discharge from satellites (Gleason and Smith, 2014). However, sampling bias and differences in post-processing create inconsistencies across HG studies that can make comparisons difficult. Additionally, recognizing and accounting for the effects of geometric channel variability and complexity has generally been omitted from traditional HG sampling such that the resulting HG exponents and coefficients may not adequately represent the range of channel hydraulics.

Current technology allows for meter-scale topographic mapping (e.g., Brasington et al., 2000; Hilldale and Raff, 2007; Williams et al., 2014) and multidimensional hydrodynamic modeling (e.g., Horritt and Bates, 2002; Zhang and Shen, 2008) of rivers, yielding sufficient data for a novel, alternative approach that could comprehensively represent the state of a river without all the problems caused by estimation through sampling. The term 'near-census' is used herein to refer to comprehensive, spatially explicit, process-based approaches using the 1-m scale as the basic building block for investigating rivers in the light of the emerging abundance of meter-scale topographic data sets without the confounding problems associated with sampling. The concept of a 'near-census' implies that meter-scale data represents variables in great detail that approaches the population of conditions, but that there remains a finer level of detail in the domain of continuum mechanics that eventually will be resolved with further technological developments. For example, decimeter-scale terrain variability captured using airborne terrestrial LiDAR has been shown to contain hydraulically relevant information in urban settings (Sampson et al., 2012; Ozdemir et al., 2013). The overall goal of this study was to present such a new approach (termed 'hydraulic topography' (HT) to differentiate it from conventional cross section HG relations), report the results of applying it to a sizable river segment, and then evaluate differences between HG and HT analyses. In addition, this study tested key traditional HG sampling methods to show significant uncertainties in contrast to common perceptions.

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1.1. At-a-station hydraulic geometry basics

Hydraulic geometry relations are power functions relating wetted channel width (W), mean flow depth (D), and mean velocity (V) to discharge (Q):

$$W = aQ^b \quad D = cQ^f \quad V = kQ^m \qquad (1)\text{–}(3)$$

where a, c, k, b, f, and m are parameters (Leopold and Maddock, 1953). When constructed for changes in discharge over time at one cross section, Eqs. (1–3) address how channel geometry accommodates changing discharge. Beginning with a triangular channel cross section, changing exponents of Eqs. (1) and (2) bends cross-sectional shape, while changing coefficients stretches it (Wyrick and Pasternack, 2008). Continuity requires that $a \cdot c \cdot k$ and $b + f + m$ both equal unity at a channel cross section, but not when derived from multiple transects with different shapes.

The idea that the HG of long river domains of varying depth and width can be reasonably represented with limited cross-sectional data is prevalent (Wolman and Brush, 1961; Langbein, 1964; Stewardson, 2005). Yet, it is also acknowledged that the mean state of a river is difficult to determine because of high variability between cross sections (Knighton, 1975; Rhodes, 1977). Differences in at-a-station HG have been observed between riffles and pools (Knighton, 1975, 1998), braided and nonbraided rivers (Knighton, 1974; Rhodes, 1977), and on the basis of variable bed substrate (Williams, 1978; Xu, 2004), bank vegetation (Andrews, 1984), and bank cohesion (Knighton, 1974).

1.2. Uncertainties in at-a-station hydraulic geometry

Despite extensive use of HG, few studies address the assumptions or explain the procedural steps in sufficient detail for repeatability. Sampling, as a paradigm for hypothesis testing in the scientific method, is inherently biased and fraught with confounding complexities relating to study-specific choices, many of which may go unexplained or unsupported in the literature for many reasons (Fig. 1). A detailed explanation is presented in the supplemental materials, Section 1.2. A complex array of interdependent factors influence HG relations, yet authors commonly assume HG exponents are acceptable because they fall within the range of globally (Jowett, 1998) or regionally (Andrews, 1984) reported values. Studies from around the world yielded ranges for at-a-station HG exponents b, f, and m of 0.0–0.59, 0.06–0.73, and 0.07–0.71, respectively; from the same at-a-station data set ($n = 139$), the modal class for b, f, and m was 0.0–0.1, 0.3–0.4, and 0.4–0.5, respectively (Park, 1977). Several study comparisons discuss the variation between HG exponents (Knighton, 1975; Park, 1977; Singh, 2003; Xu, 2004) but offer little explanation of the limitations associated with those data sources or their comparability. Based on the lack of HG details and the frequency of cross-study HG comparisons, one may conclude that geomorphologists assume the methodology is consistent. Knighton (1975) suggested a systematic selection of stable cross sections based on similar geometry and bank material to reduce variability. However, if the goal is to characterize rivers as they actually exist, including the full range of natural variability, then it is important to sample traditionally avoided transects.

1.3. Spatial scale challenges

Characterizing HG with transect sampling strategies is challenging because attributes and metrics vary with spatial scale. Herein, spatial scales are defined as segment (~10^3–10^4 W), reach (~10^2–10^3 W), and morphological unit (~10^0–10^1 W). At the segment scale, Pitlick and Cress (2002) sampled cross sections every 1.6 km along 260 km of the Colorado River. At the reach scale, two approaches commonly used have been (i) sampling in proportion to the abundance of morphological units (Rosgen and Silvey, 1996) and (ii) weighting by the distance between cross sections (Jowett, 1998; Stewardson, 2005; Navratil and Albert, 2010). According to Navratil and Albert (2010), major uncertainties associated with characterizing larger sections of river are related to river choice, its length, the number of cross sections surveyed, and the range of flows considered. At the morphological unit scale, single cross sections have been used when analyzing pool and riffles (Richards, 1976a, b).

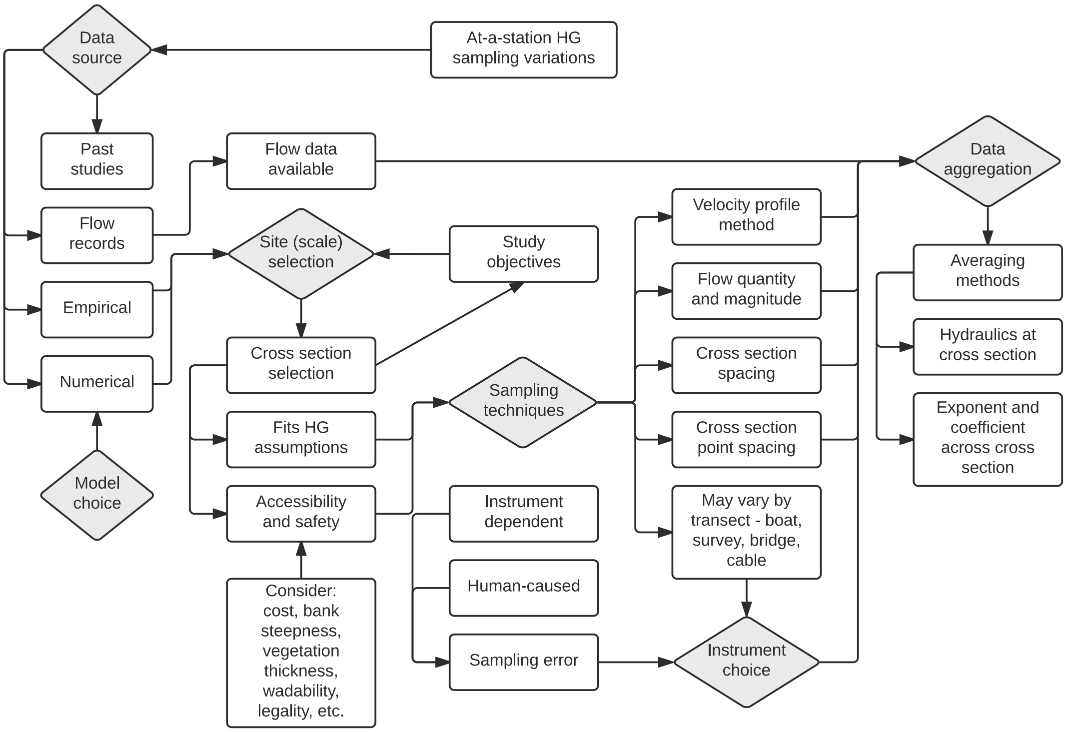

Fig. 1. A schematic that shows the complex array of considerations involved in generating at-a-station hydraulic geometry relationships. Few of these decisions are ever reported. See supplemental materials Section 1.2 for detailed explanation.