Geomorphology 122 (2010) 39–55

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Low-flow hydraulic geometry of small, steep mountain streams in southwest British Columbia

Donald E. Reid [a,*], Edward J. Hickin [b], Scott C. Babakaiff [c]

[a] BC Hydro, 6911 Southpoint Drive, Burnaby, British Columbia, Canada V3N 4X6
[b] Department of Geography, Simon Fraser University, Burnaby, British Columbia, Canada
[c] BC Ministry of Environment, Ecosystems Section, Surrey, British Columbia, Canada

ARTICLE INFO

Article history:
Received 5 May 2009
Received in revised form 20 May 2010
Accepted 24 May 2010
Available online 4 June 2010

Keywords:
Hydraulic geometry
Mountain streams
Low-flow
Habitat

ABSTRACT

This investigation explores the at-a-station hydraulic geometry (AHG) of small, steep mountain streams at low discharge. Thirteen reaches in five tributaries of Chilliwack River, British Columbia, ranging in size from 12 to 77 km^2 are examined. The resulting data set is composed of eight to twelve measurements of water-surface width, mean depth, and mean velocity at each of 61 cross sections or 625 unique combinations of the three variables. Mean velocity in a given cross section responds most rapidly to changing discharge, and 31 of the 61 cross sections have velocity exponents that are greater than the water-surface width and mean-depth exponents combined. The velocity exponent (m) averages 0.51, while the mean water-surface width exponent (b) and mean-depth exponent (f) average 0.20 and 0.29, respectively. Somewhat surprisingly, the AHG of steep mountain streams can be reasonably predicted from just a few measurements of the primary flow variables and stream discharge. While conditions at the cross section appear predictable from a few measurements, extrapolating the results from one cross section to another in the same reach involves large errors. The section-to-section variability of the exponents and coefficients, even when they are located in similar channel units such as riffles, prevents accurate extrapolation to unmeasured cross sections.

1. Introduction

This work explores the hydraulic geometry of small, steep mountain streams at low discharge (the lower quartile of the discharge range). In this range of flow, the study of hydraulic geometry can be thought of as the quantitative description of how stream discharge fills an essentially non-deformable boundary. The stream channel is self-formed at relatively high flow (arguably bankfull discharge) and its size and shape, as described by the hydraulic geometry, are governed by a set of imposed constraints that include the stream discharge (Q), sediment supply (Q_s), sediment calibre, and geomorphic history (Hey, 1978; Knighton, 1998, p. 2). In steep mountain streams the valley slope and boundary materials (coarse and even non-alluvial in places) impose additional constraints on the channel morphology that make mountain streams unique and unlike their lowland counterparts (Jarrett, 1984, 1990; Grant et al., 1990; Rice and Church, 1996; Montgomery and Buffington, 1997; Wohl and Wilcox, 2005; Comiti et al., 2007; Wohl, 2007).

Hydraulic geometry has been explored widely and remains a core technique of river science (Knighton, 1998). Despite this widespread use, the study of hydraulic geometry remains an essentially empirical enterprise because we lack universal flow resistance and sediment transport relations (Church, 1980; Bathurst, 2002). The term was coined by Leopold and Maddock in their seminal 1953 work quantitatively describing the relationship of the principal hydraulic variables of water-surface width, mean depth, and mean velocity to changing stream discharge (Leopold and Maddock, 1953). Simple power functions remain the principal basis for describing these relationships (Leopold and Maddock, 1953):

$$w = aQ^b \tag{1}$$

$$d = cQ^f \tag{2}$$

$$v = kQ^m \tag{3}$$

where w = water-surface width (m), d = mean depth (m), v = mean velocity (m/s), and Q = stream discharge (m^3/s). If there is flow continuity,

$$Q = wdv \tag{4}$$

$$Q = aQ^b cQ^f kQ^m = ackQ^{(b+f+m)} \tag{5}$$

* Corresponding author. Tel.: +1 604 528 1426, +1 604 813 8507(Cell); fax: +1 604 528 2940.
E-mail addresses: donald.reid@bchydro.com, dereid@alumni.sfu.ca (D.E. Reid).

0169-555X/$ – see front matter
doi:10.1016/j.geomorph.2010.05.012

Remarkably, this model has remained the foundation of descriptions of river form and process, for over almost a half century of modern science (Clifford, 1996).

Since 1953 the technique has been applied worldwide (Park, 1977) largely to determine the degree to which rivers respond to different sets of imposed constraints in varied geographic settings. Hydraulic geometry has also often been employed as an environmental and engineering design tool. Recent applications include the definition of instream flow standards (e.g., minimum environmental flow) that are set to minimize the impact of water use on fish populations (Jowett, 1998; Babakaiff, 2004). These applications have focussed attention on the lack of data in steep mountain settings and lack of understanding of low-flow hydraulics. Contributing to this data need constitutes a primary purpose of this work.

Frequently, flow variables of hydraulic geometry are calculated from data collected during a range of "typical" flows centred near the middle of the discharge range (Park, 1977). This practice likely reflects the desire to understand the formation and maintenance of channels and stream morphology as they relate to sediment entrainment and erosion of the channel boundary. Yet, it is among the less frequent flows found at the upper and lower ends of the discharge range where abrupt changes in channel hydraulics (e.g., resistance at low flows, channel width at high flows) occur (Leopold and Maddock, 1953; Hogan and Church, 1989). If present, these abrupt changes (or discontinuities) are thought to appear as breaks in the slope of the log-linear relations of hydraulic geometry but are rarely measured. This study focuses on the implications of this data deficiency at the lower limits of the flow-measurement range (i.e., low flow) for the hydraulic geometry of streams in SW British Columbia.

The concept of discontinuities in hydraulic geometry is not new to the literature. Ferguson (1986) noted that discontinuities separate the hydraulic geometry of one range of flow from another by physical or hydraulic differences in the cross section in each flow range. Jowett (1997) recognized at least two discontinuities in any cross section: one where the base of the channel is just filled, a second where flow spills out of the channel at bankfull. He went on to note that such discontinuities are usually most evident in rivers of moderate gradient in well-defined channels (Jowett, 1997). Knighton (1998) argued that the AHG has at least three phases: a residual phase below the threshold for bed mobilisation, an active phase when the bed is mobile, and an overbank phase at stream discharges greater than bankfull when the floodplain becomes inundated. Low-flow hydraulic geometry describes conditions in the residual phase.

The literature contains examples of several other types of AHG discontinuities. Hogan and Church (1989) in their work in the Queen Charlotte Islands, British Columbia, reported a discontinuity in their relationships when flow spilled from a small inset channel onto a large lateral bar. Leopold and Maddock (1953), in their initial work on hydraulic geometry, described a discontinuity at an artificial cross section with bridge abutments. They showed that increases in low-flow discharge filled the bed of the channel until the flow had filled the available width between the bridge abutments, leading to a new relation above this point where width remained constant and subsequent increases in stream discharge led to larger increases in mean flow depth and velocity. Hickin (1995) described a discontinuity in the plot of the hydraulic parameters for a cross section of the Fraser River at Marguerite, British Columbia, where general bed mobilisation and scour above a threshold discharge leads to an abrupt change in the width, depth, and velocity curves above this value. He also argued that this discontinuity is obscured in a log–log plot and that an examination of the relationship in an arithmetic plot is always an important first step of analysis. Lewis (1966) reported hydraulic geometry discontinuities at very low discharges where low flows occupy a smaller inset channel within the larger channel and the

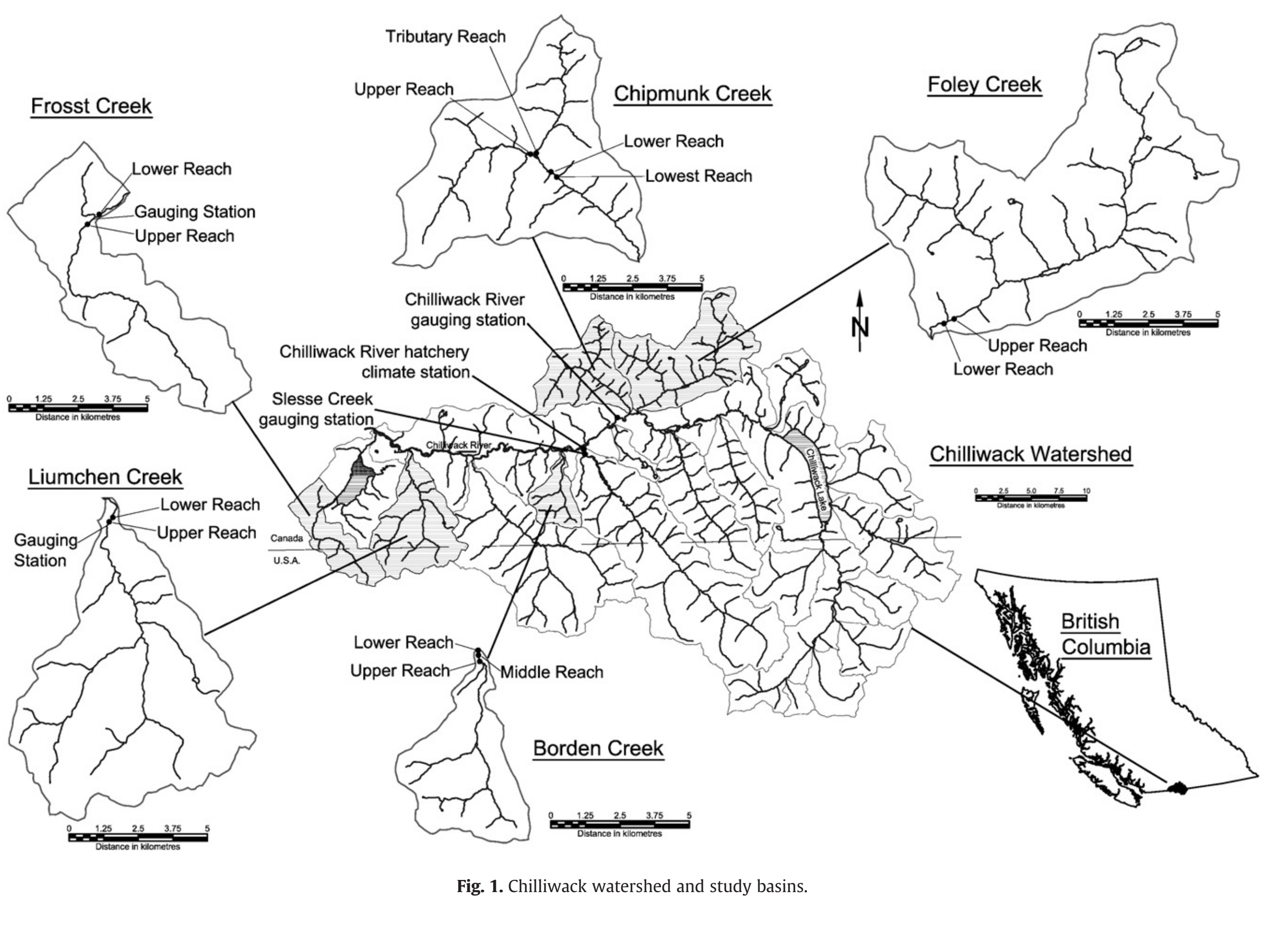

Fig. 1. Chilliwack watershed and study basins.