Geomorphology 285 (2017) 260–271

Contents lists available at ScienceDirect

Geomorphology

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

# Influence of alluvial cover and lithology on the adjustment characteristics of semi-alluvial bedrock channels

Sean P. Ferguson *, Colin D. Rennie

*Department of Civil Engineering, University of Ottawa, 161 Louis Pasteur Private, Ottawa, Ontario K1N 6N5, Canada*

ARTICLE INFO

*Article history:*
Received 27 July 2016
Received in revised form 22 January 2017
Accepted 23 January 2017
Available online 27 February 2017

*Keywords:*
Semi-alluvial channels
Bedrock channels
Hydraulic geometry
Fluvial geomorphology

ABSTRACT

A growing body of research has focused on evaluating the adjustment characteristics of semi-alluvial channels containing proximate bedrock, mixed, and alluvial sections. Active orogens have been the focus of most empirical field-based studies with comparatively less focus on semi-alluvial bedrock channels located in other regions. In this study, we present an inventory of channel geometry data collected from semi-alluvial bedrock channels in Ontario and Québec, Canada, which are not subject to tectonic uplift. Data were sourced from a variety of physiographic settings, permitting evaluation of the influence of alluvial cover, lithology, and gradient on cross-sectional channel form. Our results show no substantial difference in channel width or scaling behaviour amongst bedrock, mixed, and alluvial channels included in our study, except for sedimentary bedrock channels virtually bare of alluvial cover that represent a uniquely wide, distinct subgroup. Channel gradient does not appear to exhibit any observable control on channel width amongst our study rivers, suggesting that sedimentary bedrock channels form a distinct subgroup because of lithology. Comparatively, the widths of our bedrock channels formed in igneous/metamorphic bedrock are comparable to the widths of mixed channels and alluvial channels for a given discharge and drainage area. Our findings also suggest that cross-sectional adjustment of sedimentary bedrock channels is achieved through lateral erosion of the channel banks and downward erosion of the channel bed, whereas cross-sectional adjustment of igneous/metamorphic bedrock is primarily achieved through downward erosion of the bed with limited lateral erosion of the banks.

## 1. Introduction

Post-glaciated regions at the continental-scale typically have a complexity of physiographic landforms (Gilbert, 1994). The surficial geology of these regions is often composed of arrangements of exposed bedrock and unconsolidated materials such as glacial tills, glaciofluvial deposits, clays, and silts (Ontario Geological Survey, 2010). As such, river systems that flow through post-glaciated regions typically have channels composed of a variety of cohesive and noncohesive substrates (Ebisa Fola, 2007; Ebisa Fola and Rennie, 2010; Jamieson et al., 2013; Phillips and Desloges, 2015; Whitbread et al., 2015). The Canadian landscape was almost entirely covered by glacial ice sheets during the maximum extent of the most recent glacial episode 18,000 YBP (Gilbert, 1994; Dyke, 2004). Thus, many Canadian rivers are neither fully alluvial nor fully nonalluvial but often have semi-alluvial channels with frequent longitudinal transitions between substrate types. Although semi-alluvial river systems are common throughout post-glaciated environments, including Ontario and Québec, the forms and adjustment characteristics of semi-alluvial channels have not been the focus of much detailed investigation.

### 1.1. The concept of downstream hydraulic geometry

The study of channel form typically is approached using the concept of downstream hydraulic geometry. This concept is built on extensive empirical data suggesting that channels will develop a characteristic cross-sectional form governed by the flow and that over moderately short timespans adjustments in width, depth, and velocity will fluctuate about respective mean values (Knighton, 1984). As supported by many subsequent studies, Leopold and Maddock (1953) postulated that equilibrium channel width ($w$) and depth ($d$) can be described as power functions of discharge ($Q$):

$$w = k_w Q^b \tag{1}$$

$$d = k_d Q^f \tag{2}$$

These power functions are known as downstream hydraulic geometry scaling relationships. The exponent terms ($b$ and $f$) describe the rates

---

* Corresponding author.
*E-mail addresses:* sferg016@uottawa.ca (S.P. Ferguson), Colin.Rennie@uottawa.ca (C.D. Rennie).

http://dx.doi.org/10.1016/j.geomorph.2017.01.040
0169-555X/© 2017 Elsevier B.V. All rights reserved.

at which width and depth scale with respect to discharge. The coefficient terms ($k_w$ and $k_d$) relate to the magnitude of channel width and depth. In the context of downstream hydraulic geometry, discharge is regarded as an independent scaling parameter that can be used to describe channel form. This is complementary to the general assumption that channel form is predominantly controlled by discharge, sediment flux, and the composition of the channel bed and bank materials (Leopold et al., 1964; Knighton, 1984). Researchers generally strive to develop relationships based on a characteristic discharge predominantly responsible for channel geometry. This discharge is referred to as dominant discharge or channel-forming discharge and typically is assumed to be equivalent to bankfull discharge in alluvial streams (Leopold et al., 1964; Knighton, 1984; Copeland et al., 2000). However, some studies have developed downstream hydraulic geometry relationships using other characteristic discharges below bankfull conditions (Leopold and Maddock, 1953; Wolman, 1955). Although bankfull discharge cannot be explicitly defined by a singular overarching reoccurrence interval (Williams, 1978), researchers have found that a 1- to 2-year reoccurrence interval provides a reasonable estimate and a 1.5-year return period discharge is commonly adopted as a best assumption (Wolman, 1955; Leopold et al., 1964; Knighton, 1984; Ebisa Fola, 2007).

### 1.2. Previous research in bedrock and semi-alluvial bedrock channels

The majority of hydraulic geometry studies are based on alluvial river systems where channel substrates are transported and deposited by the flow. However, researchers have demonstrated that the concept of downstream hydraulic geometry may also be applied to nonalluvial and semi-alluvial river systems to develop scaling relationships (Bomhof et al., 2015). A number of downstream hydraulic geometry relationships have been developed for channels influenced by bedrock. Some researchers have developed bedrock scaling relationships using the classic technique where a characteristic discharge is used as a scaling parameter (Tomkin et al., 2003; Wohl and David, 2008). However, the majority of researchers have used drainage area ($A$) as a substitute for discharge because discharge data are not available (Montgomery and Gran, 2001; Spotila et al., 2015; Whitbread et al., 2015):

$$w = k'_w A^{b'} \tag{3}$$

$$d = k'_d A^{f'} \tag{4}$$

The appropriateness of substituting drainage area for discharge is dependent upon the relationship between these two parameters in the study location. The assumption is that discharge positively scales as a function of drainage area according to some consistent trend (Ries, 2007). However, the relationship between discharge and drainage area has rarely been investigated in previous studies of semi-alluvial bedrock channel hydraulic geometry, which introduces a degree of uncertainty to the majority of downstream hydraulic geometry relationships developed for these channels (Wohl and David, 2008). The development of discharge-based scaling relationships for bedrock channels would be a valuable addition to a limited database.

As summarized by Knighton (1984), the majority of downstream hydraulic geometry relationships developed for alluvial channels are relatively consistent with the classic relationships proposed by Leopold and Maddock (1953). For alluvial channels, the width and depth exponent terms ($b$ and $f$) typically are ~0.5 and 0.4 respectively. Previous findings show less consistency for the coefficient terms $k_w$ and $k_d$ (Knighton, 1984). In comparison to alluvial channels, the current database of downstream hydraulic geometry relationships developed for bedrock and mixed bedrock-alluvial channels (hereafter referred to as mixed channels) is quite limited. This is especially true for bedrock scaling relationships based on discharge; to our knowledge only two discharge-based scaling relationships exist (Tomkin et al., 2003; Wohl and David, 2008). Furthermore, most researchers have focused on developing width scaling relationships alone. However, some depth scaling relationships do exist in the literature (Wohl and David, 2008; Whitbread et al., 2015). Table 1, largely derived from a summary compiled by Wohl and David (2008), presents the range of exponent and coefficient values for bedrock channels based on existing literature.

#### 1.2.1. Influence of alluvial cover

A number of researchers have attempted to describe how sediment and alluvial cover may influence bedrock and mixed channel form (Montgomery and Gran, 2001; Sklar and Dietrich, 2001, 2004; Finnegan et al., 2007; Turowski et al., 2008; Wohl and David, 2008; Johnson and Whipple, 2010; Spotila et al., 2015; Whitbread et al., 2015). Several studies have evaluated the influence of sediment on channel form by performing a direct comparison between bedrock and alluvial sections of semi-alluvial channels (Montgomery and Gran, 2001; Wohl and David, 2008; Spotila et al., 2015; Whitbread et al., 2015). In general, most studies conclude that the scaling behaviours of bedrock and alluvial channels are not substantially different (i.e., the $b$ term is the same for both channel types; Montgomery and Gran, 2001; Wohl and David, 2008). However, Whitbread et al. (2015) found a continuum of channel width scaling behaviour with respect to drainage area between bedrock, mixed, and alluvial channel dimensions with bedrock channels scaling at the lowest rate, alluvial channels scaling at the greatest rate, and mixed channels scaling at an intermediate rate. Although Wohl and David (2008) found no difference between the scaling rate of bedrock and alluvial channels, they did conclude that alluvial sections tended to be wider than bedrock sections for a given bedrock-alluvial pairing, a conclusion supported by the findings of Whitbread et al. (2015). Conversely, Spotila et al. (2015) found bedrock reaches generally to be wider than alluvial reaches in their study of the New River in the Appalachian Mountains. These inconsistencies were also reflected by Montgomery and Gran (2001) who found the relative widths of bedrock and alluvial sections to be case dependent. Nonetheless, the majority of literature suggests that, in general, increased alluvial cover promotes channel widening, and deep and narrow channels form where a limited sediment supply mobilized as bedload over bedrock (Sklar and Dietrich, 2001, 2004; Finnegan et al., 2007; Turowski et al., 2008; Wohl and David, 2008; Yanites and Tucker, 2010; Whitbread et al., 2015). To explain this phenomenon, researchers typically comment on the duality of sediment load to behave as abrasive tools and as shielding cover in bedrock channels (Gilbert, 1877). Under conditions of low sediment supply, bedload transport tends to concentrate in the deepest portions of the channel; thus, vertical channel incision will be focused in the thalweg promoting the development of deeper and narrower channels (Finnegan et al., 2007; Turowski et al., 2008; Johnson and Whipple, 2010). Conversely, if abundant sediment supply or bed resistance induces alluvial deposition, the bed will be shielded and incision will be focused on the channel margins promoting channel widening (Sklar and Dietrich, 2001; Finnegan et al., 2007; Turowski et al., 2008; Johnson and Whipple, 2010; Yanites and Tucker, 2010).

#### 1.2.2. Influence of lithology

Unlike alluvial systems, where channel geometry is characterized by the distribution of loose sediments that are transported and deposited by the flow, bedrock channel geometry is characterized by the shape of the resistant channel boundaries sculpted through erosive processes. Although bedrock channels are self-formed by the flow, the lithologic characteristics of the channel boundaries exhibit some degree of control on the channel form (Sklar and Dietrich, 2001; Wohl and Achyuthan, 2002; Wohl and David, 2008; Allen et al., 2013; Spotila et al., 2015; Whitbread et al., 2015). In general, most research suggests that channels formed in more resistant substrates tend to be deeper and narrower than channels formed in substrates that are more easily eroded (Montgomery and Gran, 2001; Wohl and Achyuthan, 2002; Allen et