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Glacially conditioned specific stream powers in low-relief river catchments of the southern Laurentian Great Lakes

R.T.J. Phillips *, J.R. Desloges

Department of Geography, University of Toronto, 100 St. George Street, Room 5047, Toronto, Ontario M5S 3G3, Canada

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ABSTRACT

Fluvial systems of the southern Laurentian Great Lakes region are carved into a complex glacial landscape shaped by continental ice and meltwater of the late Pleistocene. These glacially conditioned river catchments are typically small with drainage areas $<10^4$ km^2. A 10-m digital elevation model (DEM) is used to map the spatial distribution of stream gradient for 22 major river catchments of peninsular southern Ontario, which drain to base levels in the lower Great Lakes (Huron, St. Clair, Erie, and Ontario). Raw data from the DEM show stream gradients that exhibit multiscale variance from real and from artifact sources. Based on a vertical slice and multiple-pass moving-window averaging approach, slope data are generalised to the river reach scale (1–2 km) as a representative spatial scale for fluvial processes operating over Holocene timescales. Models of specific stream power are then compared with glacial landform and surface geology mapping. Inherited glacial signatures in river slope appear as deviations in a stream length-gradient index (*SL*/*K* index), where river reaches are frequently oversteepened or understeepened. Based on a slope–area analysis, and complementary to theories of channel pattern discrimination, constant stream power curves (with power-law exponent of −0.4) provide a first-order approach to stratify river reaches in terms of glacial conditioning and expected planform morphologies. However, multiple-channel planform types are rare and localised in southern Ontario, indicating that oversteepened reaches with high stream powers may often be moderated by (1) sediment calibre, with cobble-beds from inherited glacial sediments; and/or (2) relative bank strength, with limited channel widening particularly in gravel and sand-bed channels. Further discrimination of glacially conditioned fluvial process domains will ultimately require consideration of alluvial floodplain characteristics in addition to general observations of river morphology and channel pattern.

1. Introduction

Fluvial systems of the southern Laurentian Great Lakes region are geologically young, carved into a landscape of complex glacial drift and subtle topography. A product of Quaternary glaciations, the Great Lakes were formed by glacial erosion of Precambrian bedrock of the Canadian Shield and overlying Paleozoic sedimentary strata of the Michigan basin. At the southern margins, late Pleistocene deglaciation deposited an extensive landscape of glacial landforms and sediments, including moraines and glaciolacustrine sequences, in the wake of the melting Laurentide continental ice sheet (Larson and Schaetzl, 2001).

Glacial conditioning of stream longitudinal profiles has been documented by recent studies for mountainous landscapes in terms of the topographic reorganisation of fluvial processes, as well as the coupling (or decoupling) of fluvial with hillslope and mass wasting processes (Fonstad, 2003; Brardinoni and Hassan, 2006; McCleary et al., 2011). The study of glacially conditioned fluvial catchments within the geologic context of past continental ice sheets in nonmountainous regions has received less attention, and any existing research has yet to be synthesised to a landscape scale. This is particularly true of the southern Laurentian Great Lakes region where the topography is subtle and the sedimentary architecture of the glacial palimpsest is vast and complex.

This paper investigates glacial signatures within river profiles of southern Ontario to extend previous research on glacial conditioning from mountainous landscapes to the low-relief catchments of the southern Laurentian Great Lakes. From river longitudinal profiles, the spatial properties of stream power are mapped within the context of glacial landforms and sediments. Previous approaches to evaluate environmental controls on river slope, and consequently channel morphology, are tested with respect to the concept of stream power, in terms of channel patterns (e.g., meandering vs. braiding; Leopold and Wolman, 1957) and fluvial process domains (Montgomery, 1999). To evaluate glacial signatures, some theory of fluvial profile evolution must be acknowledged, traditionally defined as the *graded* river profile.

2. Theoretical background

2.1. The graded river concept

The idealised concept of graded rivers is a compelling paradigm with a long history in the discipline of fluvial geomorphology (see Chorley,

* Corresponding author. Tel.: +1 416 978 3375; fax: +1 416 946 3886.
E-mail address: roger.phillips@utoronto.ca (R.T.J. Phillips).

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2000, for historical retrospective). While a graded stream is by tradition envisioned as a geometrical manifestation, a smooth longitudinal profile concave to the sky, its scientific establishment as a product of physical channel processes is largely founded on Mackin's (1948) definition that it represents the slope of transportation—the hydraulic gradient of the river is adjusted to transport the sediment supplied to it. Thus changes to the quantity and calibre of sediment supply should cause adjustments in slope produced by channel aggradation or degradation to compensate for the change, giving the concept of grade a strong connection to theories of geomorphic equilibrium and disequilibrium (e.g., Schumm and Lichty, 1965; Thorn and Welford, 1994).

In general terms, the graded river state trends downstream with systematic increases in discharge and decreases in channel slope (and sediment size), so it has also been considered to be closely associated with spatial distributions of stream power (i.e., the product of discharge and slope) (Knighton, 1999). Considerable research relies on the concept of grade or at least on the theoretical expectation of a smooth concave-up profile, most often with the assumption that it can be mathematically represented as an exponential curve (Hack, 1957, 1973; Seeber and Gornitz, 1983; Sinha and Parker, 1996; Morris and Williams, 1997; Knighton, 1999; Smith et al., 2000; Fonstad, 2003; Jain et al., 2006; Goldrick and Bishop, 2007; Barker et al., 2009; Pérez-Peña et al., 2009; Gonga-Saholiariliva et al., 2011; McCleary et al., 2011).

Since the work of Hack (1957, 1973) and Flint (1974), mathematical representations of an ideal concave-up profile regularly rely on empirical relationships of slope scaled to either river distance (L) or drainage area (A_d). Hack's (1957) equation for channel slope (S) can be summarised by

$$S = k\,L^n \tag{1}$$

where k and n are empirically derived constants, and assuming that bed material size is constant. Hack (1957) found that the case of $n = -1$ provides a useful graded profile index (or *gradient index*) for many of the Appalachian rivers he observed. This produces a simplified version of Eq. (1), where k is simply equal to the product of SL. Assuming that $n = -1$, the integrated version of Eq. (1) is of the form

$$H = C - k \ln L \tag{2}$$

where H is the channel bed elevation, and k and C are empirically derived constants. This is a straight line semilog relationship between channel elevation (linear) and channel distance (logarithmic), which represents an idealised graded profile, and has been branded by some authors as the *Hack profile* (Pérez-Peña et al., 2009; McCleary et al., 2011). For comparison of river profiles of different lengths, normalisation of the semilog profile using the graded river gradient (K) has shown to be useful for revealing profile *anomalies* relative to a theoretical SL/K index (Seeber and Gornitz, 1983; Pérez-Peña et al., 2009; McCleary et al., 2011). The normalisation factor K being the SL index, but calculated for the entire river profile as

$$K = \frac{\left(h_s - h_f\right)}{\ln\ (L_t)} \tag{3}$$

where h_s is the elevation of the drainage divide, h_f is the elevation of the river outlet, and L_t is the total length of the entire river.

The primary contribution of Flint (1974) was the equation relating channel slope (S) to drainage area (A_d) based on an empirically derived power-law:

$$S = k_s {A_d}^{-\theta} \tag{4}$$

where k_s is known as the steepness index and θ as the concavity index (Whipple, 2004; Gonga-Saholiariliva et al., 2011). Values of the concavity index (θ) tend to vary between 0.4 and 1, with the average often considered to be in the range of 0.6 (Flint, 1974; Whipple, 2004; Gonga-Saholiariliva et al., 2011). Assuming that discharge (Q) and drainage area (A_d) increase at roughly an equivalent rate, the lower range value of $\theta \approx 0.4$ from the Flint equation produces a similar relationship to that proposed by Leopold and Wolman (1957) for the slope-discharge threshold between meandering and braiding channel patterns:

$$S^* = 0.0125Q^{-0.44} \tag{5}$$

where S^* is the meandering–braiding threshold slope (Leopold and Wolman, 1957).

Criticism of the graded river concept tends to focus on the questionable universality of the smooth concave-up longitudinal profile as the ultimate state of river evolution (e.g., Phillips and Lutz, 2008; Phillips, 2011). It is essentially a concern with treating the graded river state as the normative fluvial condition, in the sense that the geometrically concave-up profile is not necessarily the most typical (i.e., exceptions may be more common than the rule) or in terms of a graded slope profile representing an ideal equilibrium steady state for the entire length of a fluvial system (but concepts of equilibrium are scale-dependent in space and time; e.g., Schumm and Lichty, 1965; Hickin, 1983; Phillips, 2011). So, at best the geometric graded river profile represents a deep property of fluvial systems (Smith et al., 2000), or at worst it represents an arbitrary benchmark (Phillips et al., 2010), from which *expected* variations in channel slope can be gauged against a conceptual standard.

The graded river concept from Mackin (1948), and his slope of transportation, seems most in tune with the ideas of geomorphic equilibrium, whereby slope is a dependent variable and is easily adjusted to spatial and temporal changes in sediment supply and calibre. However, this idea becomes troublesome if coupled with the geometric notion of smooth concave-up profiles, particularly when valley fills, sediment inputs, and bed material sizes are spatially variable and do not always trend downstream in a systematic way. Profile irregularities that may be defined as knickpoints, knickzones (Whipple, 2004; Phillips and Lutz, 2008; Phillips et al., 2010; Gonga-Saholiariliva et al., 2011), or other convex features embedded within a long profile may not be in disequilibrium if viewed at the reach scale. At reach scales, slope may be considered an independent variable over periods of years, centuries, and perhaps even millennia (Schumm and Lichty, 1965; Hickin, 1983). On the other hand, over geologic timescales of the Holocene or Quaternary, profile evolution and channel slope adjustments may tend toward some ideal form, regardless of whether or not it can ever or will ever be achieved.

The concept of the graded river profile, insofar as it represents an exponential concave-up Hack-type profile, has been demonstrated as a useful model for interpreting landscape diversity (Hack, 1973), particularly with respect to tectonic, lithological, sedimentological, glacial legacy, and base level controls on fluvial profile evolution. The assumption being that deviations from the theoretical benchmark profile represent interruptions to a graded condition (idealised by systematic trends in slope, discharge, and sediment size). Thus, the long profile may be used to tease out clues of the underlying environmental controls that complicate fluvial landscape evolution.

2.2. Specific stream power approach

In the most general physical terms, power is the rate at which energy is used, or the rate at which work is performed, expressed in units of watts (W). The concept of *stream* power thus is an expression of the potential for flowing water to perform geomorphic work, specifically in terms of sediment transport rates. As formulated by Bagnold (1966), the potential energy of water flowing downslope with gravity