VARIABILITY IN SPATIAL PATTERN OF BED ROCK INCISION

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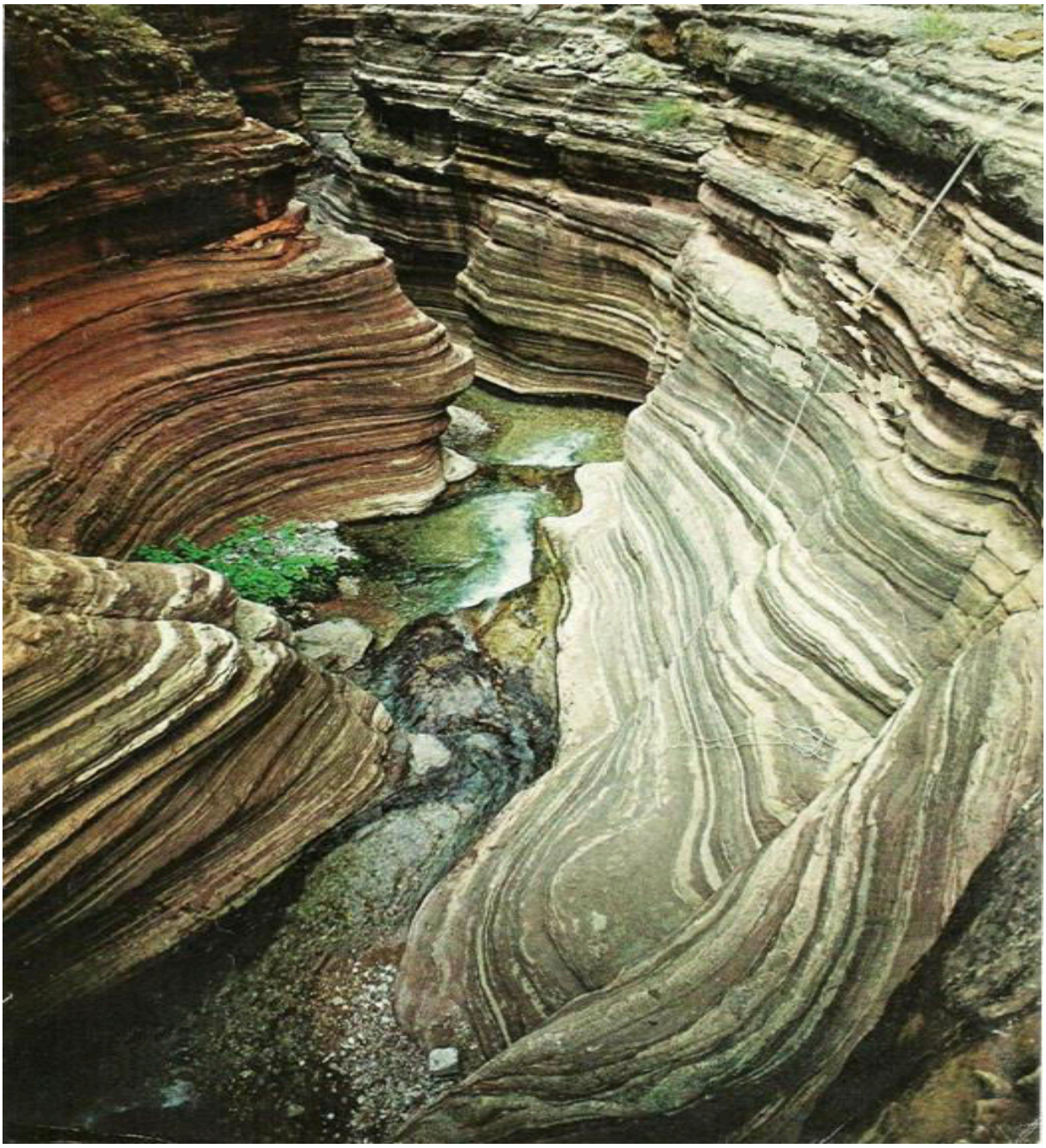

Figure.1. The Denwa River incising bedrock in tectonically active landscape, and very closer to the full downstream variability in its width.

ABSTRACT

To solve the problem of Bed rock channel incision and the evaluation of mountainous structure, well known Manning equation and basic mass conservation principles are utilized, I derive into a conclusion for scaling the steady-state width (W)*of river channels as a function of discharge* (Q)*, channel slope* (S)*roughness* (n)*, and width-to-depth ratio* (α)*:* $W = \left[\alpha(\alpha+2)^{2/3}\right]^{3/8} Q^{3/8} S^{-3/16} n^{3/8}$*. I narrate that channel width-to depth ratio, in addition to roughness, is a function of the material in which the channel is developed, and that where a river is confined to a given material, width-to-depth ratio and roughness can be assumed constant. Having seen these simplifications, the expression emulates traditional width-discharge relationships for rivers incising bedrock with uniformly concave fluvial long profiles. It is very significant that this relationship describes river width trends in terrain with spatially non uniform rock uplift rates, where conventional discharge-based width scaling laws are inadequate. I express that much of observed channel width variability in Denwa,Sonbhadra and Sonbhadra rivers(Pachmarhi,North Satpura ,India) chaannel confined by bedrock is a simple consequence of the tendency for water to flow faster in steeper reaches and therefore occupy smaller channel cross sections. I demonstrate that using conventional scaling relationships for channel width can result in underestimation of stream-power variability in channels incising bedrock and that our model improves estimates of spatial patterns of bedrock incision.*

Keywords: fluvial geomorphology, tectonic geomorphology, channel width, river incision, landscape evolution. variability.tectonically complex, steepes, spatial pattern.

INTRODUCTION

The activity of bedrock-channel incision on the evolution of mountainous topography is a central concept in geomorphology (e.g., Seidl and Dietrich, 1992; Burbank et al., 1996). Considerable attention to rivers incising bedrock in tectonically active landscapes (e.g., Whipple and Tucker, 1999) has led to the use of river morphology in interpreting the scale, magnitude, and timing of rock uplift, for which other evidence is often sparse or equivocal (e.g., Lave´ and Avouac, 2001; Finlayson et al., 2002; Kirby et al., 2003). Collectively, this work has highlighted the stream-power model of river incision as a valuable tool for exploring the dynamics of fluvial erosion of bedrock.

The stream-power model generally express bedrock incision rate, E, as a function of river slope, S, and river discharge, Q: $E = kQ^m S^n$,where k represents bedrock-specific erosivity, and m and n are empirically determined or selected on the basis of the hypothesized control on incision rate, e.g., power or shear stress (Whipple and Tucker, 1999). Estimation of river power per unit bed area or shear stress requires direct knowledge of channel width, typically approximated as bank-full channel width. However, spatially continuous width measurement necessitates high-resolution imagery and/or labor-intensive ground surveying. For this reason, models of bedrock incision often do not treat width explicitly, but instead rely on the assumption that channel width is a power-law function of discharge where$W \propto Q^b$. This substitution subsumes width variations into the exponent m on Q in the stream-power model. Substantial empirical work suggests that discharge-based width-scaling relationships are valid for alluvial rivers and that $b \approx 0.5$ (e.g., Knighton,1998). Examples where these relationship have been evaluated for bedrock channels typically exhibit exponents on area or discharge of 0.3–0.5 (e.g., Whipple, 2004).

Intensive studies based on field observations of the Pachmarhis region provide evidence for another view that Channel width varies locally, much like channel slope does, in association with spatial changes in rock uplift rate and erodibility. Lave´ and Avouac (2001) and Montgomery and Gran (2001) demonstrate downstream narrowing of river channels in bedrock associated with a downstream increase in rock uplift rate and bedrock hardness, respectively.(James A. Menking ,., Jianwei Han,., Nicole M. Gasparini and Joel P. L. Johnson 2011). Additionally, Duvall et al.(2004) showed that variation in channel width, as well as slope, can account for inferred differences in long-term fluvial incision rates between two neighboring rivers undergoing different uplift. These studies show that simple scaling relationships between width and discharge alone are not adequate in precisely those situations where it is most interesting to be able to estimate bedrock incision rates; i.e., where rates of uplift or rock erodibility vary

Figure.2. The Sonbhadra River is straitward and shows a rectangular channel. It is relatively linear and constant channel confined by bedrock and consequently the flow of water is faster in steeper reaches and occupy smaller channel.

spatially. Additionally, in an effort to provide a theoretical basis for the empirical equations of downstream hydraulic geometry,Griffiths (2003) derived a series of analytical expressions that relate

channel width, roughness, depth, slope, and discharge. However, because the analysis relies on the constraint that width scales linearly with downstream distance, the Griffiths model cannot address the downstream narrowing of channels. Generally, it remains unknown whether adoption of the traditional assumptions of hydraulic geometry has hindered understanding of the coupling between bedrock incision and tectonic processes

The incising bedrock model evaluate for the Denwa, Sonbhadra and Bainganga rivers that are incising bedrock under both uniform and spatially variable rock uplift (Fig :1). Under the simplifying assumption of constant channel width-to depth ratio and Manning's *n*, I compare how conventional width scaling laws and our proposed model predict spatial patterns in erosive potential when incorporated in a stream-power calculation. I conclude that bedrock channel width varies with both discharge and river slope, and that scaling channel width with only discharge, as is common, underestimates unit stream power in areas where rivers steepen downstream (Fig:2).

MODEL

The Manning (1891) equation, which is vastly accepted as an empirical flow law for rough, steady, and uniform channel flow, states that the cross-section average water velocity, U, is given by:

$$U = R^{2/3} S^{1/2} / n, \tag{1}$$

where R is hydraulic radius, S is bed slope, and n (Manning's n)is an empirical roughness coefficient. The hydraulic radius of the flow is its cross-section area, A, divided by the wetted-perimeter, W_{p}. For a rect-angular channel where bank-full width, W, and depth, D, are related by the width-to-depth ratio $\alpha = W/D$ (referred to hereafter as α), area and wetted perimeter are easily rewritten in terms of bank-full channel width

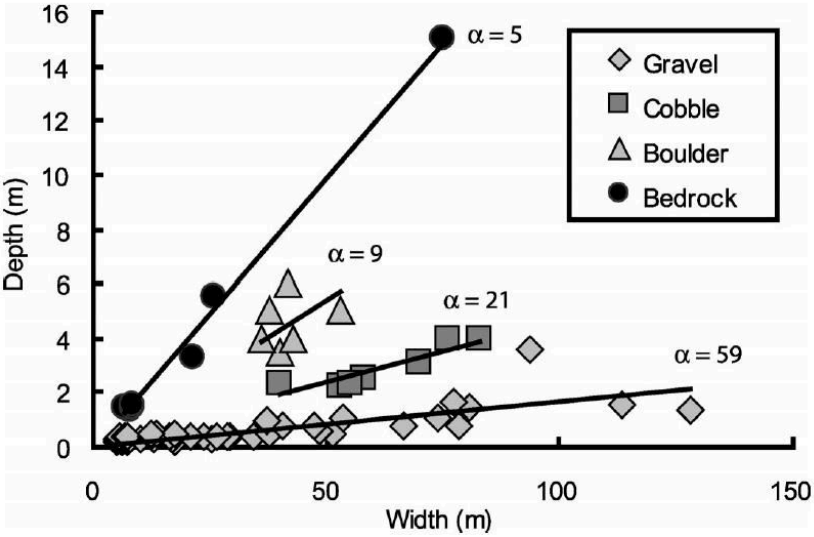

Figure 3. Plot of α for different dominant channel substrates. Gravel data are from Denwa River of Satpura, and largest bedrock width data point is from Sonbhadra River of Pachmarhis. Other data are from field surveys in the Pachmarhis region. While gathered from various locations, all bedrock data are from channels incised in high-grade Deccan Trap rocks.

$$W_{\mathrm{p}} = W + 2D = W(2/\alpha + 1), \tag{2}$$

$$A = {W^2}/{\alpha}. \tag{3}$$

Substituting equations 2 and 3 for R in equation l and simplifying yields

$$U = (\alpha + 2)^{-2/3} W^{2/3} S^{1/2} / n. \quad (4)$$

It is obvious to show that equation 4, although derived here for a rectangular channel of Pachmarhis region(Fig:2), is valid for all rivers where W and R are linearly related, i.e., for channels where α is constant. In natural channels, α appears to be relatively constant for a given channel-bed material (Fig.3), suggesting that the assumption of constant width-to-depth ratio is an acceptable simplification for a channel developed in a particular material. From mass conservation, the flow discharge can be expressed as $Q = UA$. multiplying equations 4 and 3 and solving for W therefore leads to

$$W = \left[\alpha(\alpha + 2)^{2/3}\right]^{3/8} Q^{3/8} S^{-3/16} n^{3/8}. \quad (5)$$

Equation 5 is described that channel width naturally gets increased with discharge, as is widely recognized for Pachmarhis drainage network. The equation explicitly incorporates the effects of α and n, the latter of which by impeding flow increases cross-section area. The equation also states that width can decrease with increasing channel slope, creating the potential for narrowing of channels where rivers steepen, e.g., where they enter regions with faster rock uplift rates or more resistant rock (e.g., Seeber and Gornitz, 1983; Kirby et al., 2003).

METHODS

I examined the model predictions for two relatively simple, concave-up streams incising bedrock and undergoing spatially uniform uplift. . I have tested model against data from the bedrock-channel part of the more complex Bainganga River in eastern Pachmarhis of Satpura, where it traverses a major anti formal uplift in the eastern Satpura syntaxis. As it crosses this structure, the river steepens and narrows considerably within its bedrock gorge.

I restricted my analysis of the Denwa to the Pachmarhis region where it is clearly incising bedrock and sampled width every 100 m from a continuous map of channel width created by digitizing channels from 28.5 m pixel resolution Landsat 7 Thematic Mapper images of the river at high flow. Channel elevation profiles and slopes are derived from satellite and topo map of the Pachmarhi. Mean annual discharge is obtained by routing annually accumulated data by AEC of Pachmarhi. Estimates of discharge, data have been shown to agree with gauged mean annual discharges for Pachmarhi catchments region. Due to the relatively coarse sediment, it was necessary to segment the river into 1 km reaches in order to remove noise in the river elevation profile. For each reach, mean elevation, mean channel width, and slope were calculated.

I have used field-measured bank-full width data for rivers Sonbhadra and Bainganga. Elevation and slope data are derived from 10-m-resolution digital elevation data as reported in setelite imagery. I calculated mean width, elevation, and slope for every 3 data points in the data set, resulting in mean values spaced at roughly 100 m intervals. Mean annual discharge was estimated for Sonbhadra and Bainganga by applying the relationship between mean annual discharge and drainage area.

Anomalies in slope data for all rivers were calculated using the root mean square error of 7 m for the 10-m-resolution and 18 m for 3-arc-second-resolution. These uncertainties were propagated through the various calculations of mean width and mean stream power below and are represented in the figures. It is important to keep in mind that the uncertainties shown in the figures apply only to values averaged over 10 km for the Denwa, and roughly 1000 m for the rivers in the Sonbhadra.

MODEL EVALUATION

The Denwa, Sonbhadra and Bainganga Rivers have incised their way through the tough Basalt flows into the underlying sedimentary rocks. This incising process was most rapid in the vicinity of the slope and scarp where incising was greatest (CrookShank, H.1936, Dongre. N. L, 1997 and 2012) process like many rivers incising bedrock exhibit relatively simple, concave-up elevation profiles, where slopes

decrease steadily in a downstream direction. For this class of rivers, elevation profile data can be fit into the form

$$S = kQ^{-\theta}, \tag{6}$$

where θ is referred to as the concavity index (Flint, 1974). Substitution of equation 6 into 5 yields the following expression for the dependence of the width of a river on concavity and discharge, with constant α:

$$W \propto Q^{3/8\,+30/16} n^{3/8}. \tag{7}$$

For a typical concavity index of ½ and constant roughness, equation 7 yields

$$W \propto Q^{15/32} \approx Q^{0.47} \tag{8}$$

The rivers with uniform concavities, the model measures for the discharged-based downstream width relations typically observed for alluvial channels. More significantly, the similarity of our relationship to traditional width empiricisms is confirmed for bedrock channels after plotting measured channel width, channel width determined from equation 5 with constant n and $a\left(kQ^{3/8}S^{-3/16}\right)$, and channel width determined from assuming width scales with $Q^{1/2}$along Sonbhadra and Bainganga in the Pachmarhi (Fig.4). Notably, the simplified version of equation 5 is indistinguishable from a simple relationship in which width scales only with. $Q^{1/2}$

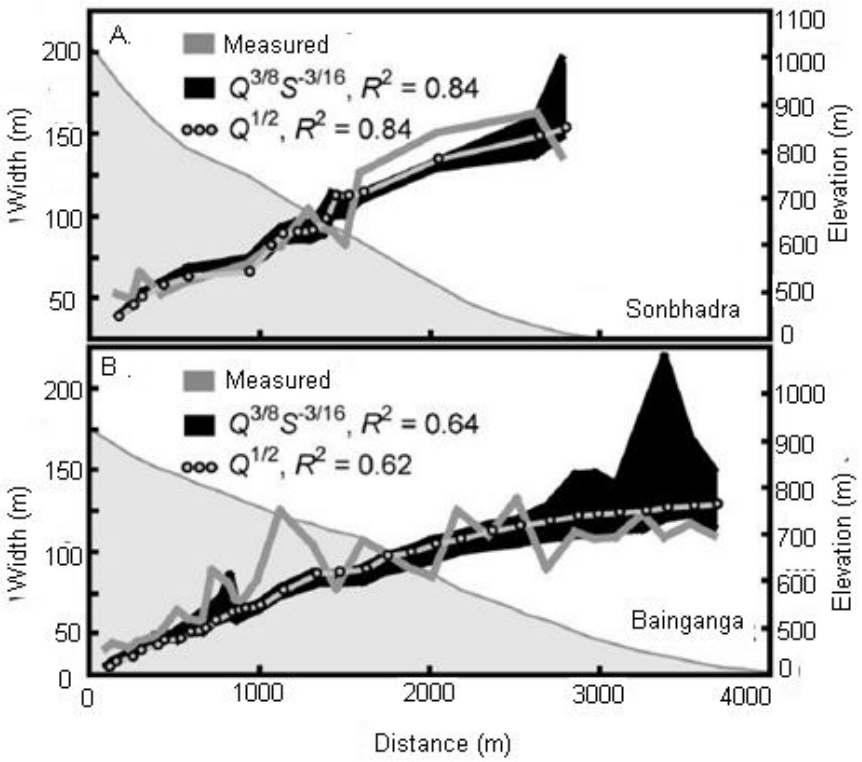

Figure 3. Profiles on long River and comparisons of channel width. Channel width derived from a $Q^{1/2}$relationship, and channel width derived from equation 5 for Sonbhadra (A) and Bainganga (B). Uncertainties due to errors in width measurement and digital elevation model–derived river slopes are represented by line thickness.

Equation 5 also predicts that anomalously steep reaches will have higher water velocities—provided that changes in channel bed roughness do not offset those in slope—and, in order to conserve water flux, smaller cross sections. Under the assumption of constant a, channel width and depth are

proportional to the square root of cross-section area, and so these reaches should be both shallow and narrow. Rivers incising bedrock in tectonically active or lithologically variable regions frequently lack consistent and uniform concavities, and local convexities are commonplace (Seeber and Gornitz, 1983; Kirby et al., 2003). In such locales, equation 5 indicates that simple width-discharge scaling relations should lose their predictive power.

To evaluate this analytical prediction in more tectonically complex terrain, I applied this model to the Denwa River. For the Denwa, I have calculated linear regressions (forced through the origin) of measured channel width vs. $Q^{1/2}$ and of measured channel width vs. $Q^{3/8}S^{-3/16}$ (equation 5 with constant n and a). For the Denwa, regression of width against $Q^{3/8}S^{-3/16}$ yielded better fits (R^2 =0.68) than did a model that scaled width with only $Q^{1/2}$ (R^2 =0.40) (Fig. 4A). The extent to which our model matches the data supports the idea that channel shape tends toward self-similar adjustments when confined to bedrock. These changes depend primarily on discharge and slope, which are externally modulated by factors such as regional base level, rock uplift rate, bedrock resistance to erosion, and climate.

RIVER INCISION MODEL

Analysis of Denwa, Sonbhadra and Bainganga river profile, which typically based on width-discharge scaling relationships, have become an important tool for inferring spatial and temporal patterns in rates of bedrock incision and, where steady

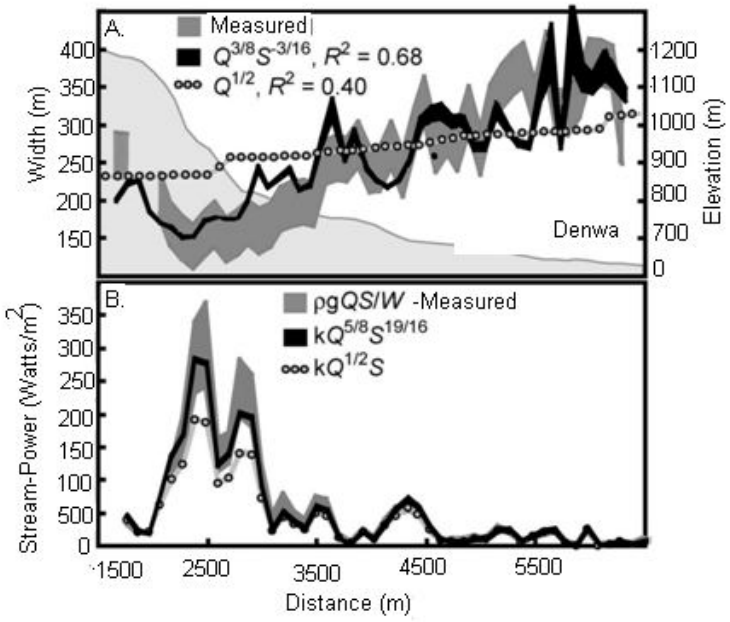

Figure 4.: A River long profile and comparison of measured channel width, channel width derived from a $Q^{1/2}$ ***relationship, and channel width derived from equation 5 for Denwa . B: Comparison of unit stream powe*** $r(\rho gQS/W)$ ***for Denwa using measured channel width, width derived from equation 5, and width derived from*** $Q^{1/2}$ ***relationship. Uncertainties due to errors in width measurements and digital elevation model–derived slopes are represented by line thickness for both A and B.***

state is assumed, rates of rock uplift (Isaac. J Larsen David R. Montgomery 2011) In order to explore the sensitivity of river incision models to different methods for estimating channel width, I compared how conventional width scaling laws and our model predict spatial patterns in unit stream power (Fig.4 B). For the Denwa, unit stream power $(\Omega = \rho gQS/W)$was calculated using mean annual discharge, slope, and channel width obtained in three ways: (1) measured; (2) determined from a conventional width

relationship of the form $W \propto Q^{1/2}$,which yields an expression of the form $kQ^{1/2}S$; and (3) determined from equation 5, which with constant *n* and a, yields an equation that takes the form

$$\Omega = kQ^{5/8}S^{19/16}. \quad (9)$$

For the Denwa, use of a simple width-discharge scaling law results in as much as a 40% underestimate of unit stream power along the sections of the river that steepen downstream. In general, such an approach also tends to damp the spatial variability in erosive power because it does not reflect the tendency for channels to narrow where they steepen. Equation 5 comes closer to describing the full downstream variability in the width of the Denwa and hence the actual unit stream power (Fig. 4 B). This model thus has important implications for fluvial responses to variable rock uplift and lithology, which are of particular interest in most active orogens. Because width appears to narrow as slope increases, a channel requires less of a change in slope (and therefore fluvial relief) than it would if slope, alone, responded to a particular forcing such as rock uplift rate, bedrock resistance to erosion, or climate. This tendency for channels to narrow as they steepen thus provides a negative feedback on fluvial relief change and results in the nonlinear exponent on slope in equation 9.

DISCUSSION

Equation 5 highlights the relative complexity of modeling channel width when flow velocity is considered. However, the Denwa, Sonbhadra and Bainganga rivers incision models make implicit assumptions about velocity. For example, Whipple and Tucker (1999) assumed that roughness is constant by inserting the dimensionless friction factor, C_f, from their momentum equation into the rate constant, K, in their erosion equation. In addition, in their derivation width is assumed to vary only with discharge. These constraints force flow depth, and therefore α, to accommodate all variation in cross-sectional area due to changes in velocity dictated by the momentum equation. Although this model was clearly not developed with the intention of predicting reach-scale morphology, it provides an example of how stream-power models make implicit requirements of the morphology of rivers. In order to explore the particular phenomenon of width scaling observed in bedrock channels, I have explicitly coupled width and depth in our analysis, and thereby allow changes in cross-sectional area to be accommodated by both depth and width. While I provide justification that α remains relatively constant for channels confined to a particular material (Fig.3), I acknowledge the fundamental control that our choice of treating the width-to-depth ratio imposes on the scaling of behavior of channel width in our analysis. Given the lack of a clear consensus on the controls on width-to-depth ratio in natural channels, I stress that other ways of scaling a can easily be accommodated in our framework. Nonetheless, equation 5 should be applied cautiously, as it requires that *R* (hydraulic radius) and *W* (channel width) be linearly related.

From (Fig.3) it is also clear that significant changes in Denwa, Sonbhadra and Bainganga river channel width are to be expected at boundaries between different types of channels, for example where a river transitions from alluvium to bedrock. Such width transitions do not result from flow velocity changes alone, and it is for this reason that I avoid alluvial reaches in our analysis. I speculate that the systematic changes in a shown in Figure 3 reflect different critical shear stresses for mobilization or erosion of channel boundaries developed in different materials. Specifically, bedrock channels can support much higher wall shear stresses than gravel channels (Fig:2). Hence a river can likely maintain a narrower channel in bedrock than in gravel at the same discharge.

Due to channel roughness, bed material and caliber are inextricably linked; it is hard to consider any of these factors independently, particularly for channels with mobile beds. (Noah J. Finnegan Greg Balco 2012) Without knowledge of Manning's *n*, I have assumed in all of our regressions and modeling that *n* is constant. As noted earlier, all stream-power formulations make the same implicit assumption of constant roughness. However, there is significant work that suggests that Manning's *n* may scale strongly with bed slope in alluvial rivers. For example, (Dingman and Sharma ,1997) reported that *n* varies with bed slope to a power of 0.3– 0.4 in alluvial channels. Adoption of such a relation for roughness would

effectively cancel out any slope dependency in our model, thus reducing width to a simple function of discharge and α. This further simplification provides a good explanation for the observation that significant narrowing and changes in flow velocity are generally absent in alluvial channels (Leopold and Mattock, 1953), but it is unable to explain the downstream narrowing observed in natural channels confined in bedrock.

Whereas channel roughness can vary as bed coarsening occurs at higher shear stresses, a channel bounded by bedrock lacks an obvious mechanism to change boundary roughness as boundary shear varies. (Miguel Castilloa, Paul Bishopb, John D. Jansenc, 2013)Therefore, I suggest that for the end-member case of a channel truly confined within bedrock boundaries, increases in flow velocity and narrowing will tend to occur where channels steepen because the flow feedbacks that operate in alluvial channels are suppressed. On the Denwa, it appears that any downstream increases in roughness along the steeper reaches of the river are not sufficient to prevent flow acceleration and the 50% channel narrowing observed along the river, unless width-to-depth ratio systematically decreases downstream.

CONCLUSIONS

I have developed a scaling relationship for the width of the Denwa, Sonbhadra and Bainganga river channels that depends on channel slope, river discharge, roughness, and channel width-to-depth ratio. A simplified version of this relation applied to longitudinally simple, uniformly concave bedrock rivers mimics traditional width-discharge relations that scale river width with only the square root of discharge. However, equation 5 is considerably more versatile, as it also describes river width trends in more complex terrain with spatial variations in rates of rock uplift.

Application of conventional discharge-based width scaling relationships to bedrock channels tends to underestimate erosive power along reaches that steepen downstream. On the Denwa, unit stream power calculated with a common discharge-based power law for channel width is as much as 40% lower than estimates made from satellite-based width measurements and from our model. Our analysis indicates that modeling of bedrock channel incision would be improved simply by accounting for adjustments in channel width due to the tendency for water flowing faster through steeper reaches to occupy smaller channels.

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