Predicting gravel bed river response to environmental change~~using a physically based model~~: the strengths and limitations of a regime-based approach

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~~predict channel changes (e.g. Church, 1995)~~ empirical hydraulic geometry relations, field evidence and the typical form of relations predicting sediment transport and flow resistance (Schumm, 1971; Kellerhals and Church, 1989; Montgomery and Buffington, 1997) .

In this paper, we present and describe a ~~numerical model~~ regime-based framework that can be used to quantify the magnitude of changes in stream channel dimensions and sediment transport capacity using a physically based approach; the model can also predict potential changes in channel pattern. The model complements the existing conceptual frameworks for thinking about channel response (e.g. Buffington, 2012), rather than replacing them. The data requirements, assumptions, limitations and typical applications are all discussed.

2 Channel Grade and ~~channel stability~~Regime Theory

~~When making predictions about stream channel response, it is typically assumed that the stream is at-grade~~ The first attempts at discerning quantitative process-form relations between channel morphology and the governing conditions of sediment flux, stream flow and channel boundary conditions resulted from studies of stable canals in India. Kennedy (1895) observed that stable canals – those that were able to transport the imposed sediment loads while neither aggrading nor degrading – exhibited a power-law relation between velocity and depth wherein the coefficient and exponent were found to be site-specific. Based on this early work Lindley (1919) developed the concept of “regime”, wherein the canal geometry is adjusted to some stable configuration that, while modified locally, does not change detectably over time. The work on Indian canals was consolidated by Lacey (1930) who attempted to generalize the site-specific, empirical equations by accounting for the composition of the boundary materials. Blench (1969) further developed this method by defining separate factors describing the bed and bank composition, respectively. He also included the effect of sediment concentration in his regime formulation, after Inglis (1949) . The sets of equations presented by Lacey and Blench both predict general channel

$$\eta = \frac{Q_b}{\rho Q S_\circ} = \frac{C}{S_\circ} \tag{3}$$

Q_b is the sediment load, ρ is the fluid density, Q is the formative discharge, and C is the sediment concentration (given by $C = \rho Q_b / Q$). Maximizing η is equivalent to maximizing the sediment transport rate for a constant stream power (as proposed by White et al., 1982 is equivalent to minimizing $S_\circ$ for a constant value of Q_b (Chang, 1979) . OT recognizes that many of the previously proposed optimality criteria are equivalent, and that those that are not strictly equivalent often produce very similar results (Eaton et al., 2004) . To some extent, the state of the river will determine what parts of the system can be adjusted, which in turn influences how an optimal solution is achieved.

All rational regime approaches are based on the assumption that the system is at grade (cf. Mackin, 1948; Lane, 1957), meaning that the channel configuration is adjusted to pass the imposed sediment supply with the available discharge. This assumption is best suited to considering the response of a river reach to persistent, long-term changes, but does not consider transient responses to high intensity/short duration impacts that may temporarily drive a river system into a state of net aggradation or degradation. ~~Lane (1957)~~ Lane (1955) presents a simple qualitative statement of channel grade~~, which is a reasonable basis for understanding the possible response of a stream~~:

$$\frac{Q_b}{Q} \sim \frac{S_\circ}{D} \tag{4}$$

It states that, for rivers that are at grade, the volume of sediment supplied to the stream (Q_b) that can be transported by the available flow (Q) is positively correlated with the gradient of the stream ($S_\circ$) and negatively correlated with the texture of the sediment being supplied (D). Implicit in this relation is that the gradient of the stream at any point has been adjusted so that the long-term average sediment supply (characterized by Q_b and D) can be transported by the discharge, Q.

Eaton and Church (2011) used equations for flow resistance and bed material

The equation used to calculate G is:

$$G = \begin{cases} 5474\left[1-\frac{0.853}{\Phi}\right]^{4.5} & \Phi > 1.59 \\ \exp\left[14.2(\Phi-1)-9.28(\Phi-1)^2\right] & 1.00 \leq \Phi \leq 1.59 \\ \Phi^{14.2} & \Phi < 1.00 \end{cases} \tag{8}$$

The total transport capacity, Q_b (in m^3/s), is estimated by:

$$Q_b = W_b \left[\frac{0.0025G\left(\frac{\tau_\circ}{\rho}\right)^{3/2}}{g(s-1)}\right] \tag{9}$$

in which ρ is the density of water, g is the acceleration of gravity, s is the specific weight for bed sediment (i.e. $s = \gamma_s/\gamma$), and W_b is the width of the stream bed.

The other transport equation in the UBCRM comes from Eaton and Church (2011). Their equation is based on ratio between a dimensionless stream power per unit width, ω^* and the critical dimensionless stream power for bed entrainment, $\omega^*_\circ$. The term ω^* is calculated by the following equation:

$$\omega^* = \frac{gdS_\circ U}{[g(s-1)D]^{3/2}} \tag{10}$$

~~and $\omega^*_\circ$ is calculated~~ The critical dimensionless shear stress (θ_c) specified in the UBCRM is translated into a critical dimensionless stream power for entrainment, $\omega^*_\circ$ using:

$$\omega^*_\circ = \sqrt{8/f}\,\theta_c^{3/2} \tag{11}$$

The term U is the average stream velocity (m/s), and $\sqrt{8/f}$ is the Darcy-Wiesbach flow resistance term. The dimensionless sediment transport rate, E^*, and the total transport capacity, Q_b, are calculated using

$$E^* = \left[0.92 - 0.25\sqrt{\frac{\omega^*_\circ}{\omega^*}}\right]^9 \tag{12}$$

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Table 2: Assessing channel response to wildfire using Monte Carlo simulations

	Pre-Disturbance	Post-Disturbance			
	(1 ch.)	(1 ch.)	(2 ch.)	(3 ch.)	(4 ch.)
~~P~~ Proportion	1.0	0.44	0.40	0.15	0.01
W [m]	9.9 ± 0.4	16.3 ± 1.7	26.2 ± 2.4	36.2 ± 2.1	45.1 ± 1.3
d [m]	0.49 ± 0.01	0.41 ± 0.02	0.32 ± 0.02	0.27 ± 0.01	0.26 ± 0.01
~~Q~~ Q_b [x 10^{-3} m^3/s]	8.9 ± 1.5	8.3 ± 1.8	5.3 ± 1.6	3.8 ± 1.1	3.4 ± 0.4

Table 3: Sensitivity analysis coefficients for Fishtrap Creek

	Response Variables		
	W	d	Q_b
C_Q	0.74	0.11	1.31
$C_{S_\circ}$	0.10	-0.33	2.22
$C_{d_{50}}$	-0.15	0.08	-1.19
$C_{d_{84}}$	0.02	0.24	-0.10
C_H	-0.73	0.41	0.45