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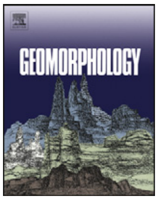

Tributary connectivity, confluence aggradation and network biodiversity

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ABSTRACT

In fluvial networks, some confluences are associated with tributary-driven aggradation where coarse sediment is stored, downstream sediment connectivity is interrupted and substantial hydraulic and morphological heterogeneity is generated. To the extent that biological diversity is supported by physical diversity, it has been proposed that the distribution and frequency of tributary-driven aggradation is important for the magnitude and spatial structure of river biodiversity. Relevant ideas are formulated within the Link Discontinuity Concept and the Network Dynamics Hypothesis, but many of the issues raised by these conceptual models have not been systematically evaluated. This paper first tests an automated method for predicting the likelihood of tributary-driven aggradation in three large drainage networks in the Rocky Mountain foothills, Canada. The method correctly identified approximately 75% of significant tributary confluences and 97% of insignificant confluences. The method is then used to evaluate two hypotheses of the Network Dynamics Hypothesis: that linear-shaped basins are more likely to show a longitudinal, downstream decline in tributary-driven aggradation; and that larger and more compact basins contain more confluences with a high probability of impact. The use of a predictive model that included a measure of tributary basin sediment delivery, rather than symmetry ratio alone, mediated the outcomes somewhat, but as anticipated, the number of significant confluences increased with basin size and basin shape was a strong control of the number and distribution of significant confluences. Doubling basin area led to a 1.9-fold increase in the number of significant confluences and compact basins contained approximately twice as many significant confluences per unit channel length as linear basins. In compact basins, significant confluences were more widely distributed, whereas in linear basins they were concentrated in proximal reaches. Interesting outstanding issues include the possibility of using spatially-distributed sediment routing models to predict tributary-driven confluence aggradation and the need to gather ecological data sufficient to properly test for increases in local and network-scale biodiversity associated with significant confluences and their network-scale controls.

1. Introduction

1.1. Tributary-driven aggradation in river networks

Confluences are nodal points of connectivity in the movement of water and sediment through a drainage network and the interaction of tributaries with their trunk streams is crucial for understanding sediment routing and maturation in river systems (Knighton, 1989; Benda and Dunne, 1997; Rice, 1998; Brierley and Fryirs, 1999; Mosley and Schumm, 2001; Fryirs et al., 2007; Fryirs, 2013). Some confluences, where tributaries supply particularly coarse and voluminous bed loads to their trunk stream, delineate “sedimentary links” that structure changes in slope, morphology and bed sediment character along individual drainage lines (Rice and Church, 1998; Rice, 1999). At these geomorphologically significant confluences, excess coarse sediment from active tributaries is stored in the mainstem channel (and associated tributary fans), forcing bed slope to steepen in order to maintain sediment dispersal downstream. Tributary-driven aggradation typically produces slope reductions and sediment fining upstream and slope steepening and sediment coarsening downstream (Miller, 1958; Church and Kellerhals, 1978; Rice and Church, 1998, 2001; Benda et al., 2004a; Harmar and Clifford, 2006; Hanks and Webb, 2006). These adjustments increase channel physical heterogeneity and, indeed, may be the primary driver of substrate, slope and morphological variability (Swanson and Meyer, 2014).

Augmentation of channel heterogeneity by tributary-driven aggradation has implications for river ecosystem functions and health because the additional habitat diversity may be an important support for biodiversity at local, reach and network scales (Benda et al., 2004b; Rice et al., 2006, 2008 for a review). Where aggradation is substantial, backwatering may produce upstream flow conditions characterised by lower velocities, deeper water and lower Froude numbers, contrasting

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with more energetic, higher Froude conditions on the steeper slope below the sediment supply point. In addition, excess sediment is available to build bedforms that add flow complexity and mesohabitats, and bed material sorting may generate diverse substrate characteristics (grain size, stability, microtopography, near-bed hydraulics) over short distances. This type of increased local heterogeneity at confluences has been associated with discontinuities in the longitudinal distribution and diversity of invertebrates (Rice et al., 2001; Knispel and Castella, 2003), periphyton and fish (Kiffney et al., 2006; Torgersen et al., 2008). In addition, the juxtaposition of contrasting physical conditions between the tributary, upstream and downstream links may offer unique opportunities for mobile taxa (Power and Dietrich, 2002), including for example, local (and therefore low-cost) access to contrasts in illumination, substrate stability, turbidity, predator avoidance and water temperature (Kupferberg, 1996; Scrivener et al., 1994; Fraser et al., 1995; Cairns et al., 2005; Katano et al., 2009; Taverny et al., 2012). There are other reasons why confluences are important for river biodiversity including: provision of nutrient or prey subsidies (Wipfli and Gregovich, 2002; Fernandes et al., 2004; Wellard Kelly et al., 2013); the presence of unique confluence-zone habitats (Nakamoto, 1994; Franks et al., 2002; Kreb and Budiono, 2005); the amplification of competition amongst species (Besemer et al., 2013); and bi-directional filtering that affects organism dispersal (e.g. Thornbrugh and Gido, 2010; Wilson and McTammany, 2014; Czeglédi et al., 2015). Confluences may therefore be biodiversity hotspots in river networks (Benda et al., 2004b), where added biological value partly reflects increased physical heterogeneity produced by tributary-forced aggradation.

However, it is clear that only some tributaries cause mainstem aggradation and measureable changes in geomorphology and ecology; many do not. Rice (1998) found that approximately 20% of tributaries along Pine and Sukunka Rivers in British Columbia had an impact on mainstem grain size or slope. It is therefore unsurprising that some evaluations of tributary impacts on stream ecology are equivocal (e.g. Milesi and Melo, 2014; Clay et al., 2015). Ultimately, this reflects the complex nature of tributary–mainstem interactions and the lack of simple systematic relations between tributary properties and their impact (Rhoads, 1987; Wallis et al., 2008). In low order streams, bedrock controls on channel geometry, disruption of sediment connectivity by wood loading and direct coupling of the channel to hillslope sediment sources may mask tributary effects (Krumbein, 1942; Miller, 1958; Benda and Cundy, 1990; Rice and Church, 1996; McEwen and Miller, 1998; Rengers and Wohl, 2007; Al Farraj and Harvey, 2010; Kuo and Brierley, 2014; Menting et al., 2015). In general, across all settings, tributary impacts on mainstem sediment storage may be transient (e.g. Kasai et al., 2005) and are contingent on local factors including degree of valley confinement, lithological variations, past depositional history and upstream sediment connectivity (Rice, 1998; Swanson and Meyer, 2014). For example, along the Sacramento River, California, basin physiography and anthropogenic interventions mean that upstream–downstream sediment connectivity is weak and tributaries devoid of sediment have no measurable impact on the mainstem (Singer, 2008).

1.2. Controls of tributary-driven aggradation — which tributaries matter?

If not all tributaries cause mainstem aggradation, but such aggradation is important, a key question is: What controls tributary-driven mainstem aggradation? Knighton (1980) argued that tributary sediment load and calibre were important determinants of step-changes in bed material grain size at confluences. Using field data from approximately 100 confluences in north-eastern British Columbia, Rice (1998) identified the product of tributary basin area and distal tributary slope ($\psi_t = A_t \cdot S_t$) and the symmetry ratio ($A_R = A_t/A_m$) as useful surrogate measures of tributary sediment delivery and relative bedload grain size, respectively (where A_t is the tributary basin area, A_m is the main stem basin area and S_t is the distal tributary slope). Logistic regression was used to establish an empirical relation for the probability of tributary impact on mainstem bed material size P_D:

$$\ln\left(\frac{P_D}{1-P_D}\right) = 8.68 + 6.08\log A_R + 10.04\log\psi_t. \tag{1}$$

Benda et al. (2004a) investigated the properties of 168 tributary confluences that had been identified as geomorphologically significant in 14 separate studies from the western United States and Canada. They found that A_R was a useful predictor of impact and defined logistic regression models for the probability of geomorphological impact P_G, for both humid and semi-arid environments, the former being:

$$\ln\left(\frac{P_G}{1-P_G}\right) = 3.79 + 1.96\log A_R. \tag{2}$$

Both models [1] and [2] suggest that the probability of a tributary impact increases with A_R, but the data sets show that the bulk of significant confluences fall in the range ($0.01 < A_R < 0.1$), such that very small tributaries, less than 1/100th of the drainage area of the mainstem, and those approaching the same size as the mainstem are less frequently important.

Benda et al. (2004a) went on to consider the factors that affect the spatial distribution of relative tributary size in a drainage basin and therefore the spatial distribution of likely impacts across river networks, identifying three key factors. First, they argued that shape should be important, with heart-shaped or compact basin shapes more likely to experience tributary impacts in distal reaches than linear, rectangular shaped basins, because the former have a higher probability of hosting relatively large tributary basins along the entire length of the mainstem. Second, they argued that more densely dissected landscapes (therefore with a higher density of confluences) should have more frequent confluence effects. Third, they pointed out that structural constraints might complicate these general relations by affecting the spacing of tributaries and the angle at which confluent channels meet, with implications for the geomorphic impact (cf. Mosley, 1976; Benda and Cundy, 1990). The role of basin shape was illustrated using predictions of confluence impact based on Eq. (2), for two sub-catchments of the Siuslaw River, Oregon, and a systematic analysis revealed an anticipated increase in the spacing between significant confluences with distance downstream along the Siuslaw mainstem. Subsequently, Benda (2008) reflected on these analyses and extended them in several ways, identifying eight testable hypotheses pertaining to the impact of tributaries on mainstem geomorphology.

In addition to this empirical work, conceptual models of alluvial regime, for example Lane (1955), and theoretical investigations for both sand- and gravel-bed rivers (Ferguson and Hoey, 2008), suggest that mainstem responses to tributaries are governed by the ratios of tributary to mainstem discharge (Q_R), bed load flux (F_R) and bed load grain size (D_R). In a numerical modelling experiment using a 1-D sediment routing model with a tributary input (TRIB), Ferguson et al. (2006) investigated the systematic variation of Q_R, F_R and D_R on mainstem geomorphology, measured as changes in channel slope and grain size. They found that patterns of bed gradation and grain-size change reflect the interplay between the sediment load that a tributary adds and the extra discharge available to transport it. Rice et al. (2006) used TRIB to explore the role of Q_R, F_R and D_R in generating physical heterogeneity around confluences, quantified as the amount of change in slope and grain size from upstream to downstream and within the upstream and downstream reaches. They found that the product $F_R \cdot D_R$ was the key determinant of such heterogeneity, while the momentum ratio Q_R was less important (Rice et al., 2006). This result is consistent with field observations showing that tributaries which introduce large amounts of relatively coarse material are associated with mainstem storage, aggradation, upstream slope reduction and downstream slope increases (e.g. Rice and Church, 1998, 2001; Swanson and Meyer,

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