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Why some alluvial rivers develop an anabranching pattern

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Abstract

Anabranching rivers have been identified globally, but a widely accepted and convincing theoretical explanation for their occurrence has remained elusive. Using basic flow and sediment transport relations, this study analyzes the mechanisms whereby self-adjusting alluvial channels can anabranch to alter their flow efficiency (sediment transport capacity per unit of stream power). It shows that without adjusting channel slope, an increase in the number of channels can produce a proportional decrease in flow efficiency, a finding particularly relevant to understanding energy consumption in some braided rivers. However, anabranching efficiency can be significantly increased by a reduction in channel width, as occurs when vegetated alluvial islands or between-channel ridges form. The counteracting effects of width reduction and an increasing number of channels can cause, with no adjustment to slope, an otherwise unstable system (underloaded or overloaded) to achieve stability. As with other river patterns, anabranching can be characterized by stable equilibrium or accreting disequilibrium examples.

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1. Introduction

[2] In contrast to braided rivers in which multiple channels are separated by subaqueous bars as part of a mobile bed within a bankfull cross section, anabranching rivers possess individual channels that are clearly separated at bankfull by subaerial vegetated islands or ridges [*Nanson and Knighton*, 1996]. However, the distinction between braided and anabranching rivers is not just with the division of channels; for a given discharge, braided rivers tend to have relatively steep gradients [*Leoplold and Wolman*, 1957], whereas anabranching rivers form over a wide range of gradients and are especially common at low slopes [*Knighton and Nanson*, 1993; *Nanson and Knighton*, 1996]. Given that most rivers flow in single channels, two obvious questions are first, why do some rivers form multiple channels and second, do multiple channel systems all form for the same reason?

[3] Studies on river systems across a wide range of environments have led to the conclusion that anabranching needs to be considered as a planform additional to the classic tripartite classification of meandering, braiding and straight [e.g., *Brice*, 1984; *Schumm*, 1985; *Knighton and Nanson*, 1993]. To examine the physical cause for anabranching, *Nanson and Huang* [1999] developed a simple mathematical model of comparative sediment transport capacities in single-thread and multiple channel systems. They showed that under conditions where gradients could not be readily increased, then the development of anabranches could enhance sediment throughput. Descriptive and quantitative studies of a variety of anabranching rivers support this contention [*Nanson and Knighton*, 1996; *Wende and Nanson*, 1998; *Tooth and Nanson*, 1999, 2000, 2004; *Tooth*, 2000; *Jansen and Nanson*, 2004]. However, *Nanson and Huang* [1999] acknowledged that not all anabranching systems would be able to enhance sediment transport to the point of achieving stable equilibrium, and subsequent research appears to support this contention as well [*Tabata and Hickin*, 2003; *Abbado et al.*, 2005].

[4] Recently, maximum flow efficiency (MFE), the maximum amount of sediment that can be transported per unit of stream power, has been found to be the product of the generally applicable variational principle of least action and to be inherent in basic hydraulic relationships for alluvial channels [*Huang and Nanson*, 2000, 2001, 2002, 2004a, 2004b; *Huang et al.*, 2002, 2004a, 2004b; *Huang and Chang*, 2006; *Nanson and Huang*, 2007]. The applicability of MFE in fluvial geomorphology has been supported with evidence that the most efficient channels are morphologically highly consistent with those described by both regime theory and downstream hydraulic geometry relations in a wide range of environments. Importantly, MFE unifies the concepts of maximum sediment transport capacity and minimum stream power which have been argued to be of fundamental importance to river studies [e.g., *Kirkby*, 1977; *Chang*, 1979a, 1979b, 1980, 1985, 1988; *White et al.*, 1982]. Indeed, it formalizes and quantifies the innovative ideas of least work adopted by *Leopold and Langbein* [1962] who argued that rivers could be seen as analogous to thermodynamic systems. *Huang et al.* [2004a] presented a more generalized analysis of the role of the principle of least action in all types of open channel flow. Within the context of this energy-based principle, they illustrated how MFE can be applied to understand quantitatively the evolutionary and operational processes leading to different river channel patterns. Although MFE has been used to explain

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the development of anabranching rivers [*Nanson and Huang*, 1999; *Jansen and Nanson*, 2004], a focus on individual cases leaves doubt as to whether it is a general characteristic that all anabranching systems are so adjusted [*Tabata and Hickin*, 2003; *Abbado et al.*, 2005].

[5] The purpose of this study is to provide a quantitative theoretical analysis of the physical causes for the development of anabranching rivers within the context of flow efficiency. It extends the variational approach advocated by *Huang and Nanson* [2000, 2001, 2002] for understanding the behavior of single-channel systems and by *Huang et al.* [2004a] for understanding the formation of river patterns. By introducing the number of channels (anabranches) as an additional variable into the basic hydraulic relationships for bed load transport in alluvial channels, it examines in detail the flow efficiency of anabranching systems under physical conditions identified from field situations.

2. Review of Theories on River Channel Patterns

[6] River patterns are commonly classified into four separate types; straight, meandering, braiding and anabranching, each a response to ongoing process of self-adjustment. These processes include channel migration and point bar formation, braid bar formation and reworking, and channel avulsion [e.g., *Leopold and Wolman*, 1957; *Bettess and White*, 1983; *Nanson and Knighton*, 1996]. River pattern and hydraulic geometry are closely related, both facilitating the dissipation or conservation of energy in some optimal way that leads to relative channel stability. Because water flowing through a bend has a higher energy loss than that in a straight channel with the same discharge, a maximum energy loss or a maximum friction factor has been argued to be the cause for the formation of meandering streams [e.g., *Jefferson*, 1902; *Schoklitsch*, 1937; *Inglis*, 1947; *Davis and Sutherland*, 1980, 1983; *Eaton and Church*, 2004]. *Leopold and Langbein* [1966] recognized that most rivers in equilibrium have a path length greater than that of the valley in which they flow. Identifying the similarities between sine-generated curves and a number of natural river meanders, they reasoned that meanders appear to be the form in which a river can be sinuous to reduce gradient and yet minimize the work it does in turning; hence they argued that this is the most probable planform a river can adopt. This minimization hypothesis, however, was regarded invalid because of the independence between total work and the flow path. Alternatively, both least time rate of potential energy dissipation and minimum stream power hypotheses have been proposed [*Yang*, 1971; *Chang*, 1979a, 1979b, 1980, 1985, 1988].

[7] In contrast to those optimal hypotheses pursued in the broad context of channel form adjustment, a number of studies have been concerned largely with the stability of the operating processes of flow within a reach. They have shown that, under the influence of a low-amplitude periodic perturbation, flow in straight channels is unstable for the transport of sediment; relatively narrow channels are more unstable in relation to meander-like perturbations and wide shallow channels are unstable in relation to braid-like perturbations [*Engelund and Skovgaard*, 1973; *Parker*, 1976; *Fredsoe*, 1978].

[8] Physically, a stable channel pattern in erodible alluvium implies the achievement of a stable equilibrium at which certain determinable relationships can be exhibited among interacting hydraulic and sedimentological variables. This has led to numerous empirical studies that distinguish river channel patterns by focusing on the development of an appropriate quantitative relationship between channel slope and flow discharge and the variant forms of this relationship [*Leopold and Wolman*, 1957; *Lane*, 1957; *Chitale*, 1973; *Begin*, 1981; *Carson*, 1984; *Ferguson*, 1984, 1987; *Bridge*, 1985; *Miller*, 1988; *Van den Berg*, 1995; *Alabyan and Chalov*, 1998; *Xu*, 2004].

[9] While alluvial channel patterns are explained largely on the basis of endogenous adjustments in flow resistance and sediment transport dynamics, there is widespread recognition that they are also the product of exogenous factors imposed on a reach by the physical environment. These factors are independent of endogenous flow conditions and yet can constrain the self-adjusting hydraulic (endogenous) variables, including width, depth, slope and flow velocity. They include not just valley slope, but also valley width and sinuosity, and the river's boundary conditions other than those formed by its mobile boundary (i.e., riparian vegetation, alluvium from a prior flow regime, colluvium, glacial or lacustrine deposits, peat, bedrock, etc.). Valley gradient is such a factor that has been widely recognized [e.g., *Schumm*, 1977; *Bettess and White*, 1983; *Schumm and Winkley*, 1994; *Eaton and Church*, 2004; *Huang et al.*, 2004a; *Tooth and Nanson*, 2004].

[10] Bank strength is another important exogenous factor and its effects on the formation of river channel patterns have been quantified with several integrated models [e.g., *Wang and Zhang*, 1989; *Millar*, 2000; *Eaton and Church*, 2004]. Because of the complication of integrating a bank stability criterion into endogenous flow relations, these models are largely computationally based. As a result, they present only the direct outcomes of the effects, such as the resultant bank angle, and have not made clear the self-adjusting mechanism of river channel flow underlying the outcomes.

[11] A wide valley and the growth of dense riparian vegetation with associated entrapment of fine sediment on the banks and between-channel ridges, appear to be essential for the development of sand load anabranching rivers [e.g., *Wende and Nanson*, 1998; *Tooth and Nanson*, 1999, 2000, 2004; *Tooth*, 2000; *Jansen and Nanson*, 2004]. To provide a convincing physical explanation of the self-adjusting mechanism underlying the formation of anabranching rivers, this study presents a detailed mathematical analysis incorporating the effects of these exogenous factors into endogenous flow resistance and sediment transport dynamics.

3. Transport Efficiency of Flow in Fully Adjustable Channels

3.1. Basic Flow Relationships

[12] Channel flow follows the laws of flow continuity, flow resistance and sediment transport with the flow continuity law taking the form

$$Q = AV \tag{1}$$

where Q, A and V are flow discharge, channel cross-sectional area and average flow velocity, respectively.

[13] Because field observations show that anabranching rivers on the Northern Plains of arid central and northern Australia flow over largely plane beds [e.g., *Tooth and Nanson*, 1999, 2000, 2004; *Tooth*, 2000; *Jansen and Nanson*, 2004], this study adopts the following Manning-Strickler formula to embody the law of flow resistance for uniform alluvial channel flow:

$$\frac{V}{V_*} = 7.68\left(\frac{R}{d}\right)^{1/6} \tag{2}$$

where $V^* = \sqrt{gRS}$ is the shear velocity, g, R, S and d are the acceleration due to gravity, hydraulic radius, flow energy slope and the representative size of sediment composing the channel bed, respectively.

[14] Channel form and behavior are associated with bed load transport and, among numerous bed load formulae, the *Meyer-Peter and Müller* [1948] equation has been extensively and successfully applied. However, recent reexaminations of the data used for its development have shown that this equation needs to be modified to increase its accuracy [e.g., *Wong and Parker*, 2006]. Besides the provision of more reliable predictions of sediment transport capacity, the revised form provided by *Wong and Parker* [2006] is essentially consistent with the linear criterion inherent in the complex interactions among flow resistance, bed load transport and channel geometry as is indicated in the study by *Huang and Chang* [2006]. Because of these, the following formula provided by *Wong and Parker* [2006] is used in this study:

$$q_b^* = 4.93[\tau_0^* - 0.0470]^{1.6} \tag{3}$$

where q_b^* and τ_o^* are the dimensionless bed load transport rate per unit channel width and the dimensionless flow shear stress, respectively, that are defined as

$$q_b^* = \frac{q_b}{\sqrt{(\rho_s/\rho - 1)gd^3}}; \qquad \tau_0^* = \frac{\tau_o}{\gamma(\rho_s/\rho - 1)d} = \frac{RS}{(\rho_s/\rho - 1)d} \tag{4}$$

in which q_b is the dimensional bed load transport rate per unit channel width, ρ_s is the density of sediments transported, ρ is the density of water, τ_o is the dimensional flow shear stress, and γ is the specific weight of water.

3.2. Transport Capacity of Flow in a Straight Single Channel

[15] In terms of the fuzzy object method for characterizing the complex profile of river channel cross sections, *Nanson and Huang* [2007] demonstrate that rivers can be regarded generally as possessing simple rectangular cross sections with small random perturbations and that the following geometric relations pertain:

$$A = WD; \qquad R = \frac{WD}{W + 2D} \tag{5}$$

where W and D are the channel width and average depth, respectively.

[16] *Huang and Nanson* [2000, 2002], *Huang et al.* [2002, 2004a], and *Huang and Chang* [2006] show that a variational analysis of the self-adjusting mechanism of alluvial channels requires the introduction of a channel shape factor, the width/depth ratio ζ, into basic flow relationships so that the number of dependent variables can be reduced:

$$\zeta = \frac{W}{D} \tag{6}$$

[17] By combining equations (5) and (6), the following channel geometry relations can be obtained:

$$A = \zeta D^2; \qquad R = \frac{\zeta}{\zeta + 2}D \tag{7}$$

[18] Consequently, incorporating equation (7) into equations (1) and (2) yields

$$\frac{Q}{\zeta D^2} = \frac{7.68\sqrt{gS}}{d^{1/6}} D^{2/3} \frac{\zeta^{2/3}}{(\zeta + 2)^{2/3}} \tag{8}$$

which, for D as a function of ζ for given Q, S and d, becomes

$$D = \left(\frac{Q}{7.68\sqrt{gS}}\right)^{3/8} d^{1/6} \frac{(\zeta + 2)^{1/4}}{\zeta^{5/8}} \tag{9}$$

[19] This $D - \zeta$ relationship, together with relationships in equation (7), leads to

$$W = \left(\frac{Q}{7.68\sqrt{gS}}\right)^{3/8} d^{1/16} \zeta^{3/8} (\zeta + 2)^{1/4} \tag{10}$$

$$\tau_o = \gamma RS = \gamma d^{1/16} S^{13/16} \left(\frac{Q}{7.68\sqrt{g}}\right)^{3/8} \frac{\zeta^{3/8}}{(\zeta + 2)^{3/4}} \tag{11}$$

Therefore the sediment discharge for the total channel width, Q_s, is a function of Q, S, d and ζ. Only when the effect of the cross-sectional shape factor ζ is included can the sediment load Q_s be illustrated with the following relationship derived from equations (3), (10) and (11) and the relationship of $Qs = q_b W$:

$$Q_s = K_1 \zeta^{3/8} (\zeta + 2)^{1/4} \left[K_2 \frac{\zeta^{3/8}}{(\zeta + 2)^{3/4}} - K_3\right]^{1.6} \tag{12}$$

where coefficients K_1, K_2 and K_3 are defined as

$$\begin{aligned} K_1 &= 4.93\sqrt{(\rho_s/\rho - 1)g} d^{25/16} \left(\frac{Q}{7.68\sqrt{gS}}\right)^{3/8} \\ K_2 &= \frac{S^{13/16}}{(\rho_s/\rho - 1)d^{15/16}} \left(\frac{Q}{7.68\sqrt{g}}\right)^{3/8} \\ K_3 &= 0.0470 \end{aligned} \tag{13}$$

[20] From equation (12), the differential form of Q_s against the variation of ζ can be derived as

$$\frac{1}{Q_s}\frac{dQ_s}{d\zeta} = \frac{(5\zeta + 6)}{8\zeta(\zeta + 2)} - \frac{(\zeta - 2)}{8\zeta(\zeta + 2)} \frac{4.8K_2\zeta^{3/8}/(\zeta + 2)^{3/4}}{K_2\zeta^{3/8}/(\zeta + 2)^{3/4} - K_3} \tag{14}$$

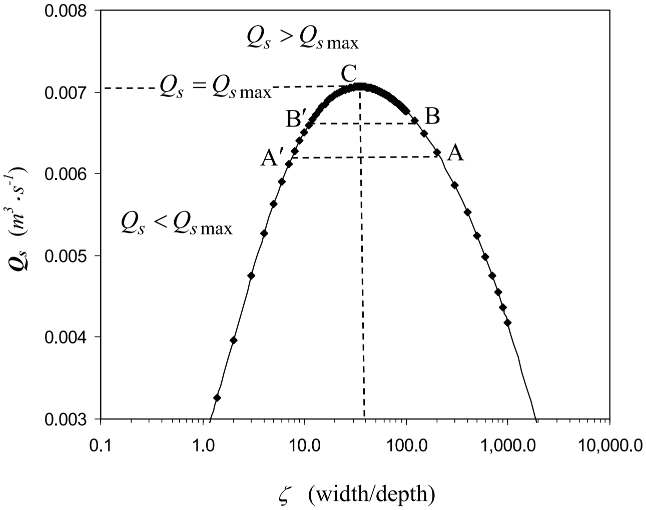

Figure 1. Variation of sediment discharge Q_s against width/depth ratio ζ (Q = 500 m^3 s^{-1}, S = 0.0002, and d = 0.8 mm).

By letting $dQ_s/d\zeta = 0$, the maximum sediment transport capacity of flow Q_{smax} can be determined from equation (14) for given S, Q and d when the following condition is satisfied at a specific point of $\zeta = \zeta_m$:

$$K_2 \frac{\zeta_m^{3/8}}{(\zeta_m + 2)^{3/4}} = \frac{5K_3(5\zeta_m + 6)}{\zeta_m + 78} \tag{15}$$

which is equivalent to

$$K_2 \frac{\zeta_m^{3/8}}{(\zeta_m + 2)^{3/4}} - K_3 = \frac{24K_3(\zeta_m - 2)}{\zeta_m + 78} \tag{16}$$

In terms of the definitions of coefficients K_2 and K_3 in equation (13), the expression of τ_o in equation (11), and the relationship of $\tau_c/[(\gamma - \gamma)d] = K_3$, equation (16) can be written simply as

$$\left.\frac{\tau_o - \tau_c}{\tau_c}\right|_{\zeta=\zeta_m} = \frac{24(\zeta_m - 2)}{\zeta_m + 78} \tag{17}$$

[21] Incorporating equation (16) into equation (12) leads Q_{smax} to be determined as

$$Q_{smax} = K_1(24K_3)^{1.6}\zeta_m^{3/8}(\zeta_m + 2)^{1/4}\left(\frac{\zeta_m - 2}{\zeta_m + 78}\right)^{1.6} \tag{18}$$

[22] It is evident in equation (18) that Q_{smax} occurs only at a specific channel geometry that satisfies equation (15) or equation (17) for the given conditions. In the situation of ζ_m = 2, the result of Q_{smax} = 0 defines the lower threshold of the most efficient alluvial channel geometry, and this is known as the best hydraulic section in an open channel without bed sediment movement. Where there is sediment movement, Figure 1 is plotted with equation (12) to show how Q_s varies with changes in ζ for flow in a straight single-channel system with specific values of Q, S and d (assuming Q = 500 m^3 s^{-1}, S = 0.0002, and d = 0.8 mm for a quantitative illustration). Under these conditions, Q_s reaches a maximum of 0.007064 m^3 s^{-1} when ζ takes a value of about 35 (point C in Figure 1).

[23] From the variation of Q_s with ζ, it is clear in theory that there are three possible states of flow in an alluvial channel: (1) $Q_s = Q_{smax}$; (2) $Q_s < Q_{smax}$; and (3) $Q_s > Q_{smax}$. As detailed in the studies of *Huang and Nanson* [2000, 2001, 2002, 2004a, 2004b] and *Huang et al.* [2002, 2004a, 2004b], the ideal case of $Q_s = Q_{smax}$ indicates that the energy of flow is just able to transport the imposed sediment load within a straight channel that has the least boundary resistance. Importantly, *Huang et al.* [2004a] demonstrated that this ideal case characterizes the special stationary equilibrium state where conditions remain the same because there is no surplus energy for flow to adjust the available channel geometry and gradient. Stationary equilibrium can be regarded as equivalent to stable equilibrium in a fluvial system because river channel flow is an iterative process which can make the stationary equilibrium state change into stable one [*Nanson and Huang*, 2007]. It is this condition that leads the regular hydraulic geometry relations exhibited in different physical environments. In the case of $Q_s > Q_{smax}$, however, there is no simple mathematical solution. This is because of an insufficient supply of energy such that, for a given sediment load in a fully adjusting system, flow will not be able to achieve equilibrium. Hence, as will be shown below, without certain exogenous conditions being imposed on the system, sediment aggradation becomes inevitable.

[24] In the case of $Q_s < Q_{smax}$, however, it is apparent from Figure 1 that in transporting a given sediment discharge Q_s, there are two solutions for channel geometry: either a wide shallow or a deep narrow channel (points A and A′, respectively, on the $Q_s - \zeta$ equilibrium curve in Figure 1). Theoretically, both solutions are able to expend the excess energy of flow so that flow is capable of achieving some form of dynamic equilibrium. However, this is not the stationary equilibrium state characterized by maximum sediment transport capacity (point C on the $Q_s - \zeta$ curve in Figure 1), so is not stable and is less efficient than the stationary equilibrium state for sediment transport. As a result, channel slope and/or cross-sectional morphology need to be adjusted and channel patterns other than straight, such as meandering and braiding, can result from [*Huang et al.*, 2004a; *Nanson and Huang*, 2007].

[25] It is also apparent in Figure 1 that if a straight single-channel system achieves dynamic equilibrium in a wide shallow channel, such as point A on the $Q_S - \zeta$ equilibrium curve in Figure 1, then without adjusting channel slope it can enhance its sediment transport capacity considerably simply by narrowing to reduce its width/depth ratio. This can be demonstrated graphically in Figure 1 by moving point A to point B on the $Q_s - \zeta$ curve. However, this reduction in channel width/depth ratio is limited by the optimum width/depth ratio (point C on the $Q_s - \zeta$ curve in Figure 1). This is because the sediment transport capacity of flow will drop when the reduced width/depth ratio passes through point C and moves to point B′ along the $Q_s - \zeta$ curve shown in Figure 1.

3.3. Transport Capacity of Flow in a Straight Multichannel System

[26] Provided multichannel rivers possess simple rectangular cross sections that have equal width and equal depth

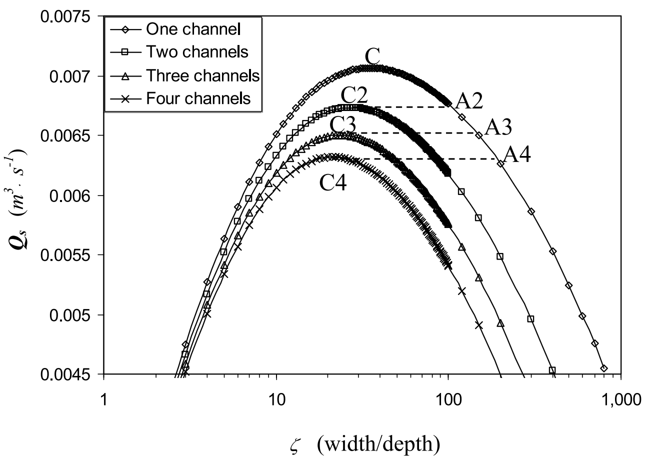

Figure 2. Variation of sediment discharge Q_s against the number of channels and the width/depth ratio ζ of each individual channel (Q = 500 m^3 s^{-1}, S = 0.0002, and d = 0.8 mm).

in each channel, and they have uniform boundaries (i.e., each boundary is of the same homogeneous alluvium not reinforced by riparian vegetation), the sediment transport capacity in the whole anabranching system can still be described with equations (12) and (18), and yet in both equations ζ becomes the width/depth ratio of individual channels and coefficients K_1 and K_2 need to be redefined in the following:

$$K_1 = 4.93\eta^{5/8}\sqrt{(\rho_s/\rho - 1)g}d^{25/16}\left(\frac{Q}{7.68\sqrt{gS}}\right)^{3/8}$$
$$K_2 = \frac{S^{13/16}}{(\rho_s/\rho - 1)d^{15/16}}\left(\frac{Q/\eta}{7.68\sqrt{g}}\right)^{3/8} \tag{19}$$

where η is the number of channels.

[27] Figure 2 is plotted to show the variation of Q_s with possible changes of ζ (width/depth ratio of individual channels or W/D) in multiple channel systems for given Q, d and S. It can be seen that with an increase in the number of channels, η, the total sediment transport capacity of flow in the multiple channel system, or $(Q_{smax})_\eta$ decreases significantly, which can be described qualitatively as

$$(Q_{smax})_1 > (Q_{smax})_2 > (Q_{smax})_3 > \ldots > (Q_{smax})_\eta > (Q_{smax})_{\eta+1} > \ldots \tag{20}$$

where $(Q_{smax})_1$, $(Q_{smax})_2$, $(Q_{smax})_3$, $(Q_{smax})_\eta$ and $(Q_{smax})_{\eta+1}$ represent the sediment transport capacity for single, two, three, η and $\eta + 1$ channel systems, respectively.

[28] Consequently, the optimal width/depth ratio of individual channels becomes progressively less, from about 35 to 20 (from point C to points C2, C3 and C4 in Figure 2) for specific values of Q, S and d (Q = 500 m^3 s^{-1}, S = 0.0002, and d = 0.8 mm). This is because ζ_m is related to coefficient K_2 which is a function of η, as shown in equations (15) and (19). To resolve the mathematical relationship between $(Q_{smax})_\eta$ and η, equations (15) and (19) can be written as

$$K_2 = \zeta_m^{\alpha_1} \tag{21}$$

where α_1 can be obtained from the following approximate power relationship:

$$\zeta_m^{\alpha_1} = \frac{(5\zeta_m + 6)(\zeta_m + 2)^{3/4}}{(\zeta_m + 78)\zeta_m^{3/8}} \tag{22}$$

When equation (22) is combined with the expression of K_2 in equation (19), the following proportional relationship is obtained:

$$\zeta_m^{\alpha_1} \propto \eta^{-3/8} \tag{23}$$

In a similar approximate form, equation (18) for a multichannel system can be written as

$$(Q_{smax})_\eta \propto \eta^{5/8}\zeta_m^{\alpha_3} \tag{24}$$

where α_3 can be obtained from the following approximate power relationship:

$$\zeta_m^{\alpha_3} = \zeta_m^{3/8}(\zeta_m + 2)^{1/4}\left(\frac{\zeta_m - 2}{\zeta_m + 78}\right)^{1.6} \tag{25}$$

Because ζ_m varies between 3 and 1000, the following approximate relationships for equations (25) and (22) are obtained:

$$\zeta_m^{3/8}(\zeta_m + 2)^{1/4}\left(\frac{\zeta_m - 2}{\zeta_m + 78}\right)^{1.6} = 0.003\zeta_m^{1.6517}; \quad r^2 = 0.9390$$
$$\frac{(5\zeta_m + 6)(\zeta_m + 2)^{3/4}}{(\zeta_m + 78)\zeta_m^{3/8}} = 0.2861\zeta_m^{0.8583}; \quad r^2 = 0.9808 \tag{26}$$

As a result, the following relationships can be obtained from equation (26):

$$(Q_{smax})_\eta \propto \eta^{\frac{5}{8} - \frac{3}{8}\cdot\frac{1.6517}{0.8583}} \propto \frac{1}{\eta^{0.0966}}$$
$$\zeta_m \propto \eta^{-\frac{3}{8}\cdot\frac{1}{0.8583}} \propto \frac{1}{\eta^{0.4369}}$$
$$(\zeta_m)_t = \eta\zeta_m \propto \eta^{1 - \frac{3}{8}\cdot\frac{1}{0.5883}} \propto \eta^{0.5631} \tag{27}$$

where $(\zeta_m)_t$ is the overall width/depth ratio of the multichannel system.

[29] To determine the optimal channel geometry in a multichannel system, one more power function relationship is required and so, when Q is replaced with Q/η, equation (10) is rewritten in the following approximated form:

$$W_m \propto \eta^{-3/8}\zeta_m^{\alpha_4} \tag{28}$$

where

$$\zeta_m^{\alpha_4} = \zeta_m^{3/8}(\zeta_m + 2)^{1/4} \tag{29}$$

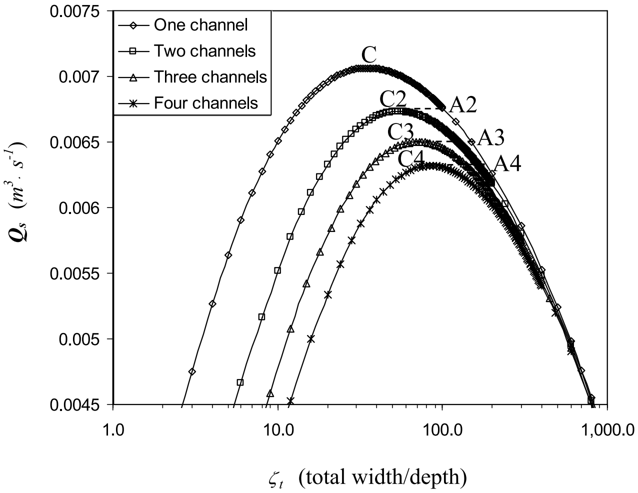

Figure 3. Variation of sediment discharge Q_s against the number of channels η and the width/depth ratio of the whole anabranching system ζ_t (Q = 500 m^3 s^{-1}, S = 0.0002, and d = 0.8 mm).

When ζ_m varies between 3 and 1000, the following approximate relationship for equation (28) is obtained:

$$\zeta_m^{3/8}(\zeta_m + 2)^{1/4} = 1.0773\zeta_m^{0.6101}; \qquad r^2 = 0.9996 \tag{30}$$

As a consequence, the combination of equations (29), (27) and (22) yields

$$\begin{aligned} W_m &\propto \eta^{-\frac{3}{8}\left(1+\frac{0.6101}{0.8583}\right)} \propto \frac{1}{\eta^{0.6416}} \\ (W_m)_t &= W_m\eta \propto \eta^{0.3584} \\ D_m &\propto \eta^{\frac{3}{8}\left(\frac{1-0.6101}{0.8583}-1\right)} \propto \frac{1}{\eta^{0.2046}} \end{aligned} \tag{31}$$

where $(W_m)_t$ is the total optimal width of the anabranching system.

[30] As is evident from equations (27) and (31) and seen in Figure 2, when the whole self-forming multichannel system in uniform material at a constant slope is at the optimal states (points C, C2, C3 and C4 in Figure 2), then with an increase in the number of channels each channel becomes narrower and deeper. Nevertheless, from Figure 3 it is apparent that the multichannel systems as a whole have larger total width/depth ratios (points C2, C3, and C4 in Figure 3) than will a single channel at the optimum state (point C in Figure 3). However, the width/depth ratios of the multichannel systems as a whole at the optimum states (points C2, C3, and C4 in Figure 3) are still smaller than the width/depth ratios of the single channels that can transport an equal amount of sediment (points A2, A3, and A4 in Figure 3). In other words, multichannel systems as a whole in their optimum states are wider and shallower than would be an optimal single-channel system, but their channels are individually much narrower and deeper than would be a single channel transporting an equal amount of sediment. Importantly, in a system with excess energy ($Qs < Q_{smax}$), the optimum multichannel system is at the most efficient state for transporting an equal amount of sediment and consumes all of the available energy and hence is more stable than the corresponding less efficient single-channel systems (points A2, A3, and A4 in Figures 2 and 3). From the notion of sediment transport efficiency, a self-adjusting anabranching system with a uniform boundary is certainly less efficient than an equivalent single-channel system, and this almost certainly explains why most fully self-adjustable rivers tend to adopt the most efficient single-channel form.

[31] The multichannel system modeled here as anabranching has completely separate channels at bankfull. Because of limited bank strength, such rivers are not known to form in unsupported homogeneous material. However, while the model is not intended for this purpose, importantly it does suggest how a braided system with surplus energy ($Qs < Q_{smax}$) incising in uniform material [*Germanoski and Schumm*, 1993] could very effectively consume surplus energy by increasing the number of braided channels until it achieves a stable or stationary equilibrium state.

[32] This increase in the number of braided channels leads to a drop in sediment transport efficiency, as illustrated graphically by moving point C in a single-channel system to point C4 in a four-channel system in Figures 2 and 3. It is apparent therefore that the gradient of a braided system needs to increase in order to achieve an equilibrium sediment transport condition equivalent to that in an optimal single-channel system. Where channel gradients cannot be significantly increased, the braided system becomes overloaded and sediment aggradation becomes inevitable. Here the development of multiple channels increases energy losses and can cause rapid deposition and associated vertical accretion, leading to unstable braided or avulsing anastomosing rivers [*Germanoski and Schumm*, 1993; *Makaske*, 2001; *Makaske et al.*, 2002; *Tabata and Hickin*, 2003; *Abbado et al.*, 2005; *Ashworth et al.*, 2007].

[33] The above model is developed for self-forming and fully adjustable multiple channels with uniform boundaries. The task remains to examine whether the model behaves differently where natural physical constraints (exogenous factors), such as low valley gradients, a wide valley and the growth of dense riparian vegetation, impact on the endogenous variables of flow resistance and sediment transport dynamics. Specifically, it needs to examine if and under what conditions the complex interactions among the endogenous and exogenous factors can make a multichannel system achieve equilibrium for transporting sediment throughput without adjusting channel gradient.

4. Exogenous Factors That Can Facilitate Efficient Channel Flow

[34] As demonstrated in the recent studies of *Huang and Nanson* [2001, 2002, 2004a, 2004b] and *Huang et al.* [2002, 2004a], endogenous flow resistance and sediment transport dynamics provide a convincing explanation of the hydrodynamic conditions that cause rivers to exhibit regular channel geometries (“regime” relations) and planforms (straight, meandering and braiding patterns). In some physical environments these conditions may not be able to be fully satisfied whereas in other environments, specific exogenous factors (such as riparian vegetation) may be necessary for a river to achieve stability.

[35] A range of anabranching conditions has now been investigated in detail in Australia and in a reach of the

Upper Columbia River, British Columbia, Canada. Because Australia is a low-relief continent, the adjustment of river slope as a means of achieving a stationary equilibrium state is in many cases greatly constrained [*Nanson and Huang*, 1999]. The Columbia River is also slope constrained because of the encroachment of tributary alluvial fans that partially obstruct the main valley [*Tabata and Hickin*, 2003; *Abbado et al.*, 2005]. While meandering rivers in unconfined material can adjust to low slopes by reducing their sinuosity and relatively increasing their energy gradients, relatively straight rivers have an option of adjusting flow characteristics by changing their cross-sectional form (channel geometry) [*Nanson and Knighton*, 1996; *Wende and Nanson*, 1998; *Tooth and Nanson*, 1999, 2000, 2004; *Nanson and Huang*, 1999; *Tooth*, 2000; *Jansen and Nanson*, 2004].

[36] In addition to low slopes, Australian rivers often exhibit cohesive fine-grained floodplain alluvium and possess highly adapted riparian vegetation that grows to near the base of the banks along channels that are frequently dry or supporting very low discharges. Hence even sandy banks can be highly stable. It has been well documented on a range of Australian anabranching rivers that channels are generally wide and shallow in the single thread reaches and narrow and deep in adjacent multithread reaches. Furthermore, the combined width of the anabranching reaches is usually less than that of the adjacent single thread reaches that are presumed, and in some cases known, to be carrying the same long-term flow discharge and sediment load [*Wende and Nanson*, 1998; *Tooth and Nanson*, 1999, 2000, 2004; *Tooth*, 2000; *Jansen and Nanson*, 2004]. This reduction in width is not the result of a downstream change in bank strength; field investigations have shown that the nature of riparian vegetation and composition of banks in the single-thread and adjacent multithread reaches remain similar. However, such banks and vegetation provide a medium within which a wide range of channel widths and boundary shear stresses can develop. When the single-thread systems divide into multichannel reaches, the multiple channels have low sinuosities and are parallel to each other, separated by narrow, flow-aligned, vegetated, channel train ridges of floodplain height, or by wider islands [*Nanson and Knighton*, 1996; *Wende and Nanson*, 1998; *Tooth and Nanson*, 1999, 2000, 2004]. In a case investigated in detail by *Jansen and Nanson* [2004], Magela Creek in northern Australia exhibited a width/depth ratio of 152 in a single-thread sandy reach whereas, in an anabranching reach immediately upstream, this ratio for individual channels was only 5 to 12, with a total width only 33% that of the single-thread reach. Such significant reductions in channel width in this sand-dominated system are accomplished by the impact of a nonuniform boundary formed of root-reinforced upper bank alluvium supporting a dense riparian corridor of monsoon forest.

[37] Upper Columbia River in British Columbia, Canada, has been regarded as the type example for river anastomosis (a term for low-energy, fine grained anabranching systems) in North America and its behavior and stratigraphy have been the subject of numerous studies over the last several decades [e.g., *Smith and Smith*, 1980; *Makaske*, 2001; *Makaske et al.*, 2002; *Tabata and Hickin*, 2003; *Abbado et al.*, 2005]. In a 120 km anastomosing reach within a 1–2 km wide valley, this river exhibits a planform of interconnected sand bed channels separated by muddy and peaty islands over a gradient of about 0.0001 that tends to decrease slightly downstream with a reduction in the number of channels. Furthermore, the slopes and summed widths of all the individual channels remain unchanged in the most anastomosing reach upstream. In a similar anabranching reach on the nearby Alexandra River in Alberta, dense riparian vegetation has been shown to increase the erosional resistance of alluvial banks 20,000 fold [*Smith*, 1976].

[38] Magela Creek and the Upper Columbia River have recently both been used to test the flow efficiency hypothesis proposed by *Nanson and Huang* [1999] for explaining the origin of anabranching rivers [*Makaske*, 2001; *Makaske et al.*, 2002; *Tabata and Hickin*, 2003; *Jansen and Nanson* 2004; *Abbado et al.*, 2005]. *Jansen and Nanson* [2004] found that, at most flows, the anabranching reach of Magela Creek is more efficient than the single-thread reach. However, they argued that not all anabranching systems would achieve such efficiency, and indeed *Tabata and Hickin* [2003] and *Abbado et al.* [2005] found that the anabranching reach of the Columbia River is a relatively inefficient disequilibrium system. The two rivers are in remarkably different physical settings so an opportunity exists to see if imposed physical constraints (exogenous factors) can produce both maximally efficient equilibrium and less efficient disequilibrium anabranching systems. The remainder of this study examines the sediment transport efficiency of flow by incorporating certain physical restrictions into the basic flow resistance and sediment transport relationships in partially adjustable channels.

5. Transport Efficiency of Flow in Partially Adjustable Channels

5.1. Basic Flow Relationships

[39] In an alluvial channel with a given width, channel depth becomes the only geometric variable that is fully adjustable. As a consequence, a combination of equations (1), (2) and (5) yields the following relationship:

$$R = \left(\frac{d^{1/6}Q}{7.68\sqrt{gS}}\frac{1}{WD}\right)^{3/2} \tag{32}$$

which leads to

$$\tau_0^* = \frac{RS}{(\rho_s/\rho - 1)d} = \frac{S^{1/4}}{(\rho_s/\rho - 1)d^{3/4}}\left(\frac{Q/W}{7.68\sqrt{g}}\right)^{3/2}\frac{1}{D^{3/2}} \tag{33}$$

By incorporating equation (33) into equation (3), sediment load Q can then be derived from the relationship of $Q_s = q_b W$ as

$$Q_s = K_1\left[K_2 D^{-2/3} - K_3\right]^{1.6} \tag{34}$$

where coefficients K_1 and K_2 are refined as

$$\begin{aligned} K_1 &= 4.93W\sqrt{(\rho_s/\rho - 1)gd^3} \\ K_2 &= \frac{S^{1/4}}{(\rho_s/\rho - 1)d^{3/4}}\left(\frac{Q/W}{7.68\sqrt{g}}\right)^{3/2} \end{aligned} \tag{35}$$

Table 1. Variation of Bed Load Transport Capacity Qs With Reductions of Channel Width W in a Single-Channel System[a]

W, m	$\frac{W-W_o}{W_o}$, %	D, m	W/D	Q_s, m^3 s^{-1}	$\frac{Q_s-Q_{so}}{Q_{so}}$, %
250	0	1.425	175.44	0.00638	0
200	−20	1.633	122.47	0.00664	4.06
150	−40	1.948	77.00	0.00689	8.01
100	−60	2.507	39.89	0.00707	10.81
75	−70	3.014	24.88	0.00703	10.19

[a] W_o is the width of the original channel and Q_{so} is the sediment discharge in the original channel.

5.2. Effects of Width Reduction in a Single-Channel System

[40] Aided by riparian vegetation, northern and central Australian rivers commonly form interchannel ridges or islands, thereby anabranching and dramatically reducing bankfull channel widths [e.g., *Wende and Nanson*, 1998; *Tooth and Nanson*, 1999, 2000, 2004; *Tooth*, 2000; *Jansen and Nanson*, 2004]. To examine the endogenous mechanism behind the width reduction, basic flow resistance and sediment transport relationships presented in equations (32) and (34) are used to assess the effects of width reduction on sediment transport capacity. For given Q, d, η, S and W, the specific value of D can then be determined for flow in each individual channel, with equation (32) being written as

$$\frac{WD}{W+2D} = \left(\frac{d^{1/6}Q/\eta}{7.68\sqrt{gS}}\frac{1}{WD}\right)^{3/2} \quad (36)$$

Because $W = W_t/\eta$, equation (36) can thus be written as

$$D^{5/2} = \left(\frac{d^{1/6}Q}{7.68\sqrt{gS}}\right)^{3/2}\frac{(W_t+2\eta D)}{W_t^{5/2}} \quad (37)$$

Hence, for given Q, d, η, S and W, the specific value of D can then be determined from equation (37) using the trial-and-error method. Using Excel and assuming Q = 500 m^3 s^{-1}, S = 0.0002, and d = 0.8 mm with η = 1 for single-channel system, it can be determined that, by letting D vary in a possible wide range from 1.200 to 3.500 m, the best fit values of D are respectively 1.425, 1.633, 1.948, 2.507, and 3.014 m with corresponding reductions in W from 250 to 200, 150, 100 and 75 m. As can be seen in Table 1, the reduction in channel width from 250 to 75 m results in a significant decrease in width/depth ratio (from 175.44 to 24.88) and causes sediment transport capacity to increase from 0.00638 to 0.00703 m^3 s^{-1}. This is about a 10% increase compared with that in the initial channel when the width/depth ratio was greater than 35 (the optimal width/depth ratio where Q_s achieves a maximum) (point C in Figures 1–3). However, below a width/depth ratio of 35, there is a progressive decline in transport capacity.

[41] This reduction in channel width can be illustrated graphically in Figure 1 by moving from point A to point B, then passing point C to point B′ along the $Q_s - \zeta$ equilibrium curve. As point C represents the width/depth ratio at which sediment transport capacity reaches a maximum, the results presented in Table 1 and Figure 1 demonstrate clearly that only when the initial channel width/depth ratio is greater than the optimal width/depth ratio for a maximum sediment transport capacity is a channel width reduction able to enhance sediment transport capacity. In contrast, when the width/depth ratio is less than the optimum, an increase in channel width is able to enhance the sediment transport capacity. This can be illustrated graphically by moving from point B′ toward point C along the $Q_s - \zeta$ equilibrium curve in Figure 1. This shows that the preexisting width/depth ratio relative to the endogenous optimum sediment transport capacity determines both the degree and adjustment direction of channel width to achieve a stationary equilibrium state.

5.3. Effects of Number of Channels

[42] As identified in the anastomosing reach of the Upper Columbia River, the cumulative channel width increases or remains roughly constant as the number of anabranches increases [*Abbado et al.*, 2005]. To reflect the quantitative effect of this on the sediment transport capacity, Q, S and d are given specific values (Q = 500 m^3 s^{-1}, S = 0.0002, and d = 0.8 mm) and the sediment transport capacity is determined with equation (34), in which coefficients K_1 and K_2 are redefined in the following forms:

$$K_1 = 4.93\eta W\sqrt{(\rho_s/\rho-1)gd^3}$$
$$K_2 = \frac{S^{1/4}}{(\rho_s/\rho-1)d^{3/4}}\left(\frac{Q/\eta}{7.68W\sqrt{g}}\right) \quad (38)$$

By keeping the total channel width at a constant 250 m, and letting the number of channels η vary from 1 to 5, from equation (37) the specific values of D can be determined. With Excel and the trial-and-error method, and letting D vary in a wide range from 1.200 to 2.800 m, it can be shown that the best fit values of D vary from 1.425 to 1.451 m with corresponding increases in η from 1 to 5. As shown in Table 2, this increase in η results in a significant decrease in the width/depth ratio (from 175.44 to 34.46) and causes the sediment transport capacity to progressively decrease from 0.00638 to 0.00600 m^3 s^{-1}, a ∼6% drop in comparison with the transport capacity in a single channel. It would decrease more if cumulative width were allowed to increase. This result is consistent with the study by *Abbado et al.* [2005] who performed similar hydrodynamic modeling of the behavior of the anastomosing reach of the Columbia River under the condition of a constant cumulative channel width.

5.4. Counteracting Effects of Number of Channels and Width Reduction

[43] As demonstrated in section 5.2, a reduction in the width of a wide shallow channel can cause an increase in

Table 2. Variation of Total Bed Load Transport Capacity Q_s With the Number of Channels η[a]

η	W_t, m	W, m	D, m	W/D	Q_s, m^3 s^{-1}	$\frac{Q_s-Q_{so}}{Q_{so}}$, %
1	250	250	1.425	175.44	0.00638	0
2	250	125	1.432	87.29	0.00628	−1.57
3	250	83.33	1.439	57.91	0.00620	−2.82
4	250	62.5	1.445	43.25	0.00611	−4.23
5	250	50	1.451	34.46	0.00600	−5.96

[a] Q_{so} is the sediment discharge in the original channel.

Table 3. Variation of Total Bed Load Transport Capacity Q_s With a 20% Reduction of Total Channel Width W_t[a]

η	W_t, m	W, m	D, m	W/D	Q_s, m^3 s^{-1}	$\frac{Q_s - Q_{so}}{Q_{so}}$, %
1	250	250	1.425	175.44	0.00638	0
1	200	200	1.633	122.47	0.00664	4.06
2	200	100	1.644	60.84	0.00651	2.10
3	200	66.77	1.654	40.29	0.00638	0.00
4	200	50	1.665	30.03	0.00626	−1.80
5	200	40	1.676	23.87	0.00614	3.71

[a]Q_{so} is the sediment discharge in the original channel.

the sediment transport capacity, while section 5.3 shows that an increase in the number of channels can lead to a decrease in this capacity. Similar trends were obtained in a laboratory flume experiment by *Jansen and Nanson* [2004]. The complex relationship between sediment transport, width reduction and the number of channels implies physically that some anabranching rivers are able to achieve a stationary equilibrium state. To understand this complex relationship, Q, S and d are given specific values (Q = 500 m^3 s^{-1}, S = 0.0002, and d = 0.8 mm) and the variation of D against the number of channels η for a given W is determined from equation (37) using the trial-and-error method. The sediment transport capacity can then be obtained from equation (34), in which the values of K_1 and K_2 are determined from equation (38). For a 20% reduction of total channel width, Table 3 shows, as in Table 1, that with a single channel, width reduction plays a dominant role such that sediment transport can be considerably enhanced. However, with an increase in the number of channels η from 2 to 4, η becomes counter productive causing the initial increase in sediment transport capacity to subsequently decrease. When η = 3, the counteracting roles of width reduction and the number of channels are balanced such that the imposed sediment load can be transported throughout without net erosion or aggradation. This implies that in situations where a river has insufficient energy (an excess bed load; $Q_s > Q_{smax}$) and the channel slope cannot be increased sufficiently, division of a single channel into two anabranches could enhance sediment movement with the anabranching system achieving stable equilibrium. However, this can only occur when an exogenous factor such as riparian vegetation enables an appropriate width reduction.

[44] Tables 4 and 5 show the changes in sediment transport capacity in an anabranching system with channel width reductions of 40% and 60%. With a 40% reduction in width, the beneficial effect on sediment transport is negated where 3 < η < 4. This demonstrates that where such a river has excess bed load ($Q_s > Q_{smax}$) and its channel slope cannot be significantly increased, the division of the single channel up to, in this case, three anabranches could enhance sediment movement and achieve stable equilibrium. With a 60% contraction, however, the threshold between width reduction and an optimum number of channels occurs at 2 < η < 4.

[45] The results in Tables 2–5 show a complex relationship between width/depth ratio and η, similar to the findings of *Nanson and Huang* [1999]. They demonstrated that anabranching rivers offer a wide range of possible conditions for achieving a stationary equilibrium state, from overloaded systems requiring a dramatic enhancement in sediment transport, to those where there is surplus energy and the multiplication of channels could expend this surplus. The results may also be important for river rectification work. There are many engineering projects which have tried to enhance sediment transport capacity by reconstructing river channels, but these have been challenged by the problem of finding an effective channel width [e.g., *Chang*, 1988].

[46] An interesting question arising from Tables 3–5 is that, if the maximum increase in transport efficiency is achieved by a simple reduction in the width/depth of a single channel and any subsequent anabranching will reduce that improvement, then why would multiple channels form at all? There are at least three possibilities. First, many anabranching systems have one dominant channel and numerous less important ones, so in fact anabranching may often be associated with most of the flow passing down what is essentially a main channel significantly reduced in width. Under such a condition, the various smaller anabranches would therefore cater mainly for the displaced water. In their study of Magela Creek, *Jansen and Nanson* [2004] found that, as a three-channel anabranching system, there was indeed a largest anabranch and that it dominated the efficiency of the overall system. *Abbado et al.* [2005] found that the smaller anabranches have their beds elevated above those of the main channels and that they only flow during higher stages. An extension of this argument is that width reduction is such an effective mechanism for enhancing sediment transport that not all the available water discharge is required for this task.

[47] Second, anabranching systems are often formed of a complex array of channels confined by vegetation, some atrophying while others are still forming. Having one or two dominant channels in operation at any one time achieves the efficiencies revealed in Tables 3–5 while the smaller channels are either in decline or, if still forming, stand ready to adopt a major role should one of the main channels become blocked with bed load or debris. In other words,

Table 4. Variation of Total Bed Load Transport Capacity Q_s With a 40% Reduction of Total Channel Width W_t[a]

η	W_t, m	W, m	D, m	W/D	Q_s, m^3 s^{-1}	$\frac{Q_s - Q_{so}}{Q_{so}}$, %
1	250	250	1.425	175.44	0.00638	0
1	150	150	1.948	77.00	0.00689	8.01
2	150	75	1.968	38.11	0.00669	4.87
3	150	50	1.988	25.15	0.00650	1.86
4	150	37.5	2.008	18.67	0.00631	−1.03
5	150	30	2.029	14.78	0.00613	−3.98

[a]Q_{so} is the sediment discharge in the original channel.

Table 5. Variation of Total Bed Load Transport Capacity Q_s With a 60% Reduction of Total Channel Width W_t[a]

η	W_t, m	W, m	D, m	W/D	Q_s, m^3 s^{-1}	$\frac{Q_s - Q_{so}}{Q_{so}}$, %
1	250	250	1.425	175.44	0.00638	0
1	100	100	2.507	39.89	0.00706	10.69
2	100	50	2.557	19.55	0.00669	4.87
3	100	33.33	2.606	12.79	0.00635	−0.52
4	100	25	2.657	9.41	0.00601	−5.75
5	100	20	2.707	7.39	0.00571	−10.55

[a]Q_{so} is the sediment discharge in the original channel.

anabranching offers a high degree of adaptability under potentially changeable conditions.

[48] Third, in disequilibrium systems such as the Columbia River, anabranching may be the most efficient means of accomplishing sediment sequestration across an extensive and rapidly aggrading floodplain. Without multiple channels and their proximally high but shared floodplain sedimentation rates, a single channel carrying the entire load, and thereby forming adjacent deep flood basins, would offer an even more unstable alternative condition. If so, there is a lesson here suggesting the retention of anabranches when managing floodplains along anabranching rivers.

[49] Where the channel width/depth ratio is larger than optimal and channel width cannot be sufficiently reduced, the formation of multiple channels can lead to a decrease in the sediment transport capacity of the system. As a result, vertical accretion may occur, and a continual process of new channel creation and old channel abandonment may turn out to be an effective way for the disequilibrium anabranching system to transport and store excess sediment. The anabranching reach of the Upper Columbia River is sequestering a remarkable 60% of its sediment load and is a prime example of such a disequilibrium system [*Tabata and Hickin*, 2003; *Abbado et al.*, 2005]. It would appear that, as with other river patterns such as braiding or meandering, anabranching can characterize stable equilibrium or accreting disequilibrium systems.

[50] Clearly, bank strength is also a very important factor influencing the adjustment of channel geometry and planform [e.g., *Wang and Zhang*, 1989; *Millar and Quick*, 1993; *Huang and Nanson*, 1998; *Millar*, 2000; *Brooks and Brierley*, 2002; *Eaton and Millar*, 2004]. However, in the examples of anabranching rivers modeled in this study (those described by *Wende and Nanson* [1998], *Tooth and Nanson* [1999, 2000] and *Jansen and Nanson* [2004]), single and multichannel reaches along each exhibit essentially uniform bank sedimentology and vegetation and therefore broadly uniform resultant bank strengths. The manyfold changes in channel width downstream in each case result from the transformation of the river from a single-thread to a multichannel system. They are not the result of changes in bank strength. In a single-thread system, a significant reduction in channel width confines the flow with the additional shear, making the banks unstable and the flow deviate away from its original uniform state. For this reason, beyond the need for the system to achieve some minimum bank strength value overall, this study does not consider bank stability as a sensitive variable for the formation of anabranches in the rivers modeled here. Nevertheless, there will almost certainly be situations where the transform of a single-channel to a multichannel system is accompanied with a change in the bank strength to a value sufficient for anabranches to form at all. Clearly, the effects of bank strength on the formation of those anabranching rivers then must be taken into account.

[51] While this study highlights the importance of exogenous factors (valley gradient and suitable riparian vegetation) on the development of river channel planform, in accordance with field observations on known anabranching rivers then the endogenous flow resistance condition considered here is a simple plane bed because the adoption of more resistant bed forms requires higher stream powers than those available. This implies that channel roughness is also an important factor to be considered in explaining mechanisms for the formation of river channel planform. For rivers with excess gradients, besides adjusting channel geometry and slope, the creation of more resistant bed forms is a way to expend excess energy. As *Chang* [1979a, 1979b] has demonstrated, rivers on steep gradients tend to develop a braided pattern so that the flow stays in the lower-flow regime and achieves greater roughness and better sediment transport efficiency.

6. Discussion and Conclusions

[52] There occurs naturally a wide variety of alluvial rivers that include braiding, meandering, straight, and anabranching patterns. The purpose of this paper has been to provide an integrated quantitative theory to explain the occurrence of alluvial anabranching systems. The explanation is based on the endogenous flow resistance and sediment transport relations in self-adjusting systems that must transport the supplied sediment load with the exact amount of available energy required to maintain stationary equilibrium. Channel slope, an endogenous variable, is widely known in many alluvial systems to adjust so as to maintain this balance, but where it cannot, perhaps because valley slopes are particularly low, some rivers can enhance their flow efficiency by developing in-channel islands and ridges to reduce channel width/depth ratios. This endogenous adjustment, however, can lead to anabranching only with the aid of suitable riparian vegetation, an exogenous variable, and in some cases with associated deposition of relatively cohesive sediments on the channel banks and islands. Indeed, there may even be cases where cohesive muddy bank alluvium, in the absence of vegetation, is sufficient [*Nanson and Knighton*, 1996]. Regardless, it is the availability of superior bank strength that helps to maintain optimum channel dimensions.

[53] By increasing the number of channels (anabranching), reductions in width/depth ratio can increase flow transport capacity. However, the relationship is complex because, beyond a certain point, an increase in the number of anabranches can in fact cause a decrease in the transport capacity. It may be therefore that anabranching is dominated by one or two major anabranches that achieve most of the transport efficiency.

[54] Importantly, the counteracting effects of width reduction and the number of channels make it possible, without adjusting channel slope, for certain anabranching systems (either underloaded or overloaded) to achieve stable equilibrium for the transport of a given sediment load. Where channel widths can be substantially reduced because of an available bank strength provided by riparian vegetation and the fine, commonly cohesive, sediment that can accumulate on such banks, then anabranching rivers can offer a significant enhancement in sediment transport capacity. When channel width cannot be significantly reduced, however, an increase in the number of channels can cause sediment transport capacity to drop considerably. This can lead to rapid vertical accretion, as shown in the anastomosing reach of Upper Columbia River in British Columbia, Canada. Along with braiding and meandering, anabranching appears to be a pattern adopted by certain rivers in order to achieve stable equilibrium. However, as with meandering

and braiding, not all anabranching rivers will exhibit stable equilibrium. Such a pattern under disequilibrium conditions can act to increase sediment distribution and sequestration across extensive rapidly accreting floodplains.

[55] Although this study shows that width reduction can lead to an increase in sediment transport capacity, there is a limit to this effect beyond which further confinement will result in a drop in the transport capacity. These findings are important for river rectification design where determining a suitable channel width has proven difficult.

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