River channel and bar patterns explained and predicted by an empirical and a physics-based method

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Abstract

A continuum of river channel patterns exists that have classically been distinguished based on empirical and physics-based predictors of sinuosity, presence of multiple bars or channels across the river and basic floodplain characteristics such as presence or absence of cohesive sediment or vegetation on islands. Formative conditions of these different patterns are not well understood and cannot yet be predicted well, neither by classical empirical nor by theoretical methods.

Our objective is to understand general causes of different river channel patterns. In this paper we compare an empirical streampower-based classification and a physics-based bar pattern predictor. We present a careful selection of data from literature that contains rivers with discharge and median bed particle size ranging several orders of magnitude with various channel patterns and bar types, but no obvious eroding or aggrading tendency.

Empirically a continuum is found for increasing specific streampower, here calculated with pattern-independent variables: mean annual flood, valley gradient and channel width predicted with a hydraulic geometry relation. ‘Thresholds’, above which certain patterns emerge, were identified as a function of bed sediment size for predictive purposes.

Bar theory predicts nature and presence of bars and bar mode, here converted to active braiding index (\(B_i\)). The most important variables are actual width-depth ratio and nonlinearity of bed sediment transport. Results agree reasonably well with data.

Empirical predictions are somewhat better than bar theory predictions. Moreover, in combination they provide partial explanations for bar and channel pattern. Increasing potential specific streampower implies more energy to erode banks and indeed correlates to channels with high width-depth ratio. Bar theory shows that these develop more bars across the width (higher \(B_i\)). At the transition from me-
andering to braiding weakly braided rivers and meandering rivers with chutes are found. Rivers with extremely low streampower and width-depth ratios hardly develop bars or meandering.

Key words: braided river, meandering river, anabranching, scroll bar, chute bar

1. Introduction

Alluvial channels classically are categorised as braided, meandering and straight (Leopold and Wolman, 1957; Ferguson, 1987; Nanson and Knighton, 1996) (Fig. 1). These patterns form members of a continuum without physical thresholds (Carson, 1984; Ferguson, 1987). In this paper we consider individual channels of an anabranching system on the continuum from straight to braided (Nanson and Knighton, 1996).

Channel pattern and the style of meandering or braiding is closely related to the nature of the bars (see Kleinhans, 2010, for review). Rivers self-organise their planform pattern through feedbacks between bars, channels, floodplain and vegetation, which emerge as a result of the basic spatial sorting process of washload sediment and bed sediment. Whilst bars and floodplain form, the banks are eroded on the other side of the channel. Thus the balance between floodplain formation and destruction determines the width of channels. Bar pattern, in turn, is determined mostly by width-depth ratio. Relatively narrow rivers may have alternate scroll bars and pointbars and are single-thread. Wide rivers with multiple bars in their cross-section have multiple channels and are therefore braided. Transitional states include weak braiding, chute bars and chute channels.

Bar patterns provide the template of bank erosion and formation as well as the dynamics of channel networks in anabranching and braiding rivers. In meander bends, bars are forced to their positions by the bends, in contrast to free bars that may migrate. It is therefore tempting to infer that alternating bars lead to alternating bank erosion so that meandering rivers emerge. But this requires that new floodplain forms on the opposite side at the same rate as it is eroded, otherwise the channel widens and transitions to a more braided state. Thus the floodplain

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Figure 1: Classification of alluvial river patterns including single channel and anabranching forms. Laterally inactive channels consist of straight and irregular sinuous forms whereas active channels consist of more regular sinuous (=meandering) and braided forms. (Modified after Nanson and Knighton, 1996).
formation by washload deposition, levee formation and vegetation enters the explanation of channel and bar pattern (Kleinhans, 2010).

Simple parameters related to the channel and unrelated to the floodplain have been used with some success for independent prediction of the pattern despite the complexity of bar-channel-floodplain interaction. One general approach was semi-empirical, wherein certain parameters for channel flow strength such as gradient, streampower or sediment mobility, were plotted for a range of rivers (see Ferguson, 1987, for review). The other approach was more physics-based, whereby the physics of flow and sediment transport were simplified to such extent that analytical solutions emerged for incipient bar or channel patterns (Parker, 1976; Fredsoe, 1978; Struiksma et al., 1985; Seminara and Tubino, 1989).

The relevance of such simple predictors is twofold. Firstly, reasonable success of simple predictors tells us that general channel pattern is a relatively simple emergent property on the full underlying complexity. Secondly, simple predictors and classifications remain useful assessment tools for river renaturalisation purposes, geological reconstruction and efficient characterisation of many rivers. Many small rivers all over the world are being renaturalised and allowed to re-meander. However, some of these rivers never meandered which could have been predicted with a simple predictor. Moreover, as hydrological and sediment transport boundary conditions changed since the historical time that those rivers were natural, their new pattern may differ from that on historical maps. The effect of such change can again be assessed by simple predictors. Furthermore many large rivers in the world are transitioning from one to another channel pattern and the simple predictors provide hypotheses for the causes. Our work on the simple predictors is not intended to replace more sophisticated modelling and experimental work; merely to feed it with new hypotheses, to compare the historically separated geomorphological and engineering approaches, and to outline the limitations of the simple predictors. Our own work in progress includes such experimental and numerical recreation of these patterns (see Kleinhans, 2010, for outline).

The first objective of this paper is to extend the van den Berg (1995) semi-empirical predictor of channel pattern to more detailed prediction of bar pattern, thereby stressing that channel patterns form a bar pattern-related continuum without hard thresholds. The second objective is to compare the empirical predictions to a simplified-physical predictor (Struiksma et al., 1985; Crosato and Mosselman, 2009) for bar pattern, in order to explore the explanatory and predictive power of the semi-empirical and physical approaches.

The setup of the paper is as follows. First the semi-empirical prediction method for channel pattern of van den Berg (1995) is outlined, followed by our
extension to bar pattern based on literature and observation. Next the physics-based prediction methods of bar stability by Struiksma et al. (1985) and number of braids by Crosato and Mosselman (2009) (based on Struiksma et al., 1985) are described. We then describe how data on natural rivers and their patterns were collected (provided as online supplementary material). The results section describes how the data supports the theory and empirical predictors and how the latter two compare. In the discussion we counter earlier criticism on the empirical discrimination, address the effect of using different predictors for channel width, and discuss the anastomosis and anabranching patterns and the relation between streampower, floodplain formation and resulting bank strength.

2. Theory

2.1. Empirical discrimination

2.1.1. The van den Berg (1995) discriminator between meandering and braiding

Streampower is a useful parameter in river pattern prediction simply because it represents the energy to move sediment (Ferguson, 1987). van den Berg (1995) developed a method of channel pattern prediction that incorporates valley slope, mean annual flood discharge and a predicted channel width by a hydraulic geometry relation (given below), so that no information of actual, pattern-dependent channel characteristics is required for the prediction. The method allows a discrimination of braided and meandering river patterns in unconfined alluvium from general pattern-independent boundary conditions of median grain size of the river bed \( D_{50} \) and a potential specific streampower (W/m\(^2\)), \( \omega_{pv} \), defined as:

\[
\omega_{pv} = \frac{\rho g Q S_v}{W_r}
\]

where \( \rho \) = water density (kg/m\(^3\)), \( g \) = acceleration due to gravity (m/s\(^2\)), \( S_v \) = valley slope (-), related to channel slope as \( S = PS_v \), \( W_r \) = reference channel width (m) and \( Q \) = channel-forming discharge (m\(^3\)/s) (mean annual flood or bankfull discharge, discussed later). Essentially, \( \omega_{pv} \) is a parameter for the potential maximum of the available flow energy corresponding to a minimum sinuosity \( P = 1 \).

The reference width \( W_r \) is predicted to remain independent of the actual, pattern-dependent width \( W_a \) as (see van den Berg, 1995, for discussion of this choice):

\[
W_r = \alpha \sqrt{Q}
\]

with \( \alpha = 4.7 \sqrt{s/m} \) for sand defined as \( D_{50} < 2 \text{mm} \) and \( \alpha = 3.0 \) for gravel.
A discriminant analysis based on a large number of river data indicated that for streampower versus median particle size of the channel bed (in m) the discriminator between dominantly braiding and meandering was found at

$$\omega_{bm} = 900D_{50}^{0.42}$$

(3)

where subscript \(bm\) indicates braided-meandering (van den Berg, 1995).

Bledsoe and Watson (2001) confirmed this empirical finding of van den Berg using logistic regression analysis. They showed that it represented the 50% probability of braiding, which again emphasises that these discriminants do not discriminate but indicate a gradual transition. Rather than streampower Bledsoe and Watson (2001) used a mobility parameter defined as:

$$M = \sqrt{QS}$$

(4)

(\(\sqrt{m^3/s}\)) and found the discriminator at

$$M_{bm} = 10^{-\beta_0+q}\frac{\beta_2}{\beta_1}D_{50}^{-\beta_2/\beta_1}$$

(5)

with coefficients (their model 72) \(\beta_0 = 12.78, \beta_1 = 8.08\) and \(\beta_2 = -2.40\). The probability distribution around this discriminator is described by the parameter \(q\):

$$q = \ln \frac{p}{1-p}$$

(6)

where \(p = \text{probability (for instance 0.1 or 0.9 for the 10% and 90% percentiles)}\). Substitution of Eq. 2 into Eq. 1 shows that the mobility parameter of Bledsoe and Watson (2001) can be reinterpreted as specific streampower wherein prediction of width is implicitly included. It comes as no surprise then that streampower and mobility parameter gave nearly exactly the same discriminator between braiding and meandering (Bledsoe and Watson, 2001). Henceforth we refer to both as the empirical method and use the streampower method.

Makaske et al. (2009) showed that the empirical method also allowed the prediction of low energy stable channels by a discriminant at a ten-fold lower streampower:

$$\omega_{ia} = 90D_{50}^{0.42}$$

(7)

where subscript \(ia\) refers to the discrimination between inactive channels and active channels with scroll bars. Inactive or stable channels are here defined as being immobile, that is, having no lateral migration because their flow energy is below the threshold to erode the bank material.
We prefer to call these stable or immobile channels rather than straight as in Leopold and Wolman (1957), as in reality many of these channels have an irregular course, some with a high sinuosity, which erroneously suggests a process of active bank erosion, lateral migration and scroll bar formation—in other words, meandering. The immobile anastomosing channels of the Columbia river are indeed straight (Makaske et al., 2002), but the nearly immobile channels on intertidal mud flats only erode their banks in the sharpest bends due to flow separation (Leeder and Bridges, 1975; Kleinhans et al., 2009). As we will argue below, it is the presence and nature of the bars, rather than sinuosity, that defines a more meaningful river pattern.

2.1.2. Discrimination between bar patterns by streampower?

Based on a number of observations we will hypothesise how and why bar pattern can be predicted from streampower. This will lead to an extension of the original diagram of van den Berg (1995), which can more directly be compared to bar theory.

In the downstream, upper part of inner meander bends three types of bars can be distinguished: scroll bars, chute bars and tail bars. Tail bars are generated in the wake of obstructions, such as large woody debris as described by (Edwards et al., 1999). Thus tail bars can be formed in all river systems, meandering or braided, irrespective flow energy conditions, so we will further disregard this type. Scroll bars and chute bars form during peak discharges in accretionary inner meander bends and emerge at low stage. Based on literature we will argue below that chute bars are associated to higher streampower whereas scroll bars may occur in low and high streampower.

A scroll bar is a curvilinear ridge to the side of the channel and more or less parallel to the channel. In planform it often points down-channel and is therefore sometimes named pointbar (Smith, 1974; Church and Jones, 1982). Yet, this is confusing as the frequently-used term pointbar in sedimentology denotes the accretional part of the inner meander bend. A pointbar extends vertically from the deepest part of the main channel to the starting point of accumulation of topstratum fines associated to floodplain formation. As such they commonly preserve transverse sorting in the channel bend as upward fining of the entire pointbar deposit.

Scroll bars can result from several processes (Nanson and Croke, 1992). The best-known and possibly most important process is their generation by landward migration and coagulation of transverse bars. Downstream the bend apex in the decelerating, slightly pointbar upslope directed component of the helical flow near
the bed. The flow over a scroll bar curves towards the inner bend, because of
difference in head between the main flow and the more or less stagnant water in
the slough behind the bar (Lewin, 1970; Ackers, 1982). As a result transverse
bars migrate upslope and are remolded into a dynamic scroll bar with a steep
downstream side almost perpendicular to the main channel flow direction (Jackson
II, 1976). In contrast to these dynamic scrolls, a more stable type of scroll bar may
form from deposition of fines from suspension (Nanson, 1980).

Active scroll bars can only form if accumulation space is created in the inner
meander by outer bend erosion. This explains their absence in rivers that are sta-
bles due to low flow energy or human interference. Scroll bars develop a wider
spacing and form more frequently as the rate of erosion of the opposed outer
channel bank increases (Hickin and Nanson, 1975). Accretion of the inner bend–
or pointbar–and formation of successive scroll bars often but not always results
in a characteristic ridge and swale topography. The curvilinear ridges of this to-
pography mark time lines of the accretion by scrolls of the upper pointbar (Tooth
et al., 2008).

Chute bars are common in braiding rivers and also occur in meandering rivers.
Chute bars are horse-hoe shaped lobes formed at the downstream end of a chute or
chute channel that crosses a braid bar at peak discharge. The flow first converges
into the chute, and diverges past the chute lobe on both sides, which therefore
agrades (Ferguson et al., 1992). Chute channels and chute bars are also common
on inner bends of in meandering rivers with relatively high specific streampower
values at peak discharge (McGowen and Garner, 1970; Gustavson, 1978; Black-
nell, 1982; Bridge et al., 1988; Fielding and Alexander, 1996; Bartholdy and Billi,
2002; Kemp, 2004). In addition they are known from several less energetic river
systems, as relict structures of former braided patterns (Marston et al., 1995).

When chutes end in chute bars they do not count as braids in the definition of
braiding and braiding intensity. Only when the growth of a chute results in a chute-
cut off, a new braid is formed. Indeed, experiments have shown that chute cutoffs
indicate the transition from meandering to braiding (Friedkin, 1945). Chute cutoff
is also an important process in active braiding (Ashmore, 1991).

Most studies that focus on chute bars do not mention dynamic scroll bars,
implicitly suggesting that they are not present and that chute bars would exclude
their formation (McGowen and Garner, 1970; Nanson, 1980; Blacknell, 1982;
Brierley and Hickin, 1991; Kemp, 2004). However, several investigations report
the occurrence of both types of bars on one and the same pointbar (Lewin, 1970;
Bridge et al., 1988; Fielding and Alexander, 1996). For instance, 18th century
maps of the Rhine near the Dutch-German border show that this river had scroll
bars as well as chute bars in association with eroding banks in the outer bends (Fig. 2). Shortly after then it was engineered into a stable navigation channel devoid of emergent bars at low flow.

The configuration of scroll and chute bars depends on the curvature of the main channel in the Allier river. In wide bends chute bars migrate downstream to about halfway the pointbar. In more tightly curved bends dynamic scroll bars generally become wider and chutes tend to crosscut most of the pointbar. Chute bars sometimes merge with scroll bars (Fig. 3), and chute bars appear to develop and reactivate relatively infrequent, depending on the recurrence of high flood events (van den Berg and Middelkoop, 2007).

To summarise, the available evidence suggests that chute bars and chute cut-offs are related to the transition between meandering and braiding at relatively high streampower just below the discriminator to braided. Chutes are therefore expected to overlap with weakly braided rivers. Scroll bars, on the other hand, are associated to actively meandering rivers at all streampowers below the discriminator of braided rivers and above that of stable rivers. Thus the energy-based classification of river patterns can be detailed further with discriminators between immobile rivers without bars ($< \omega_{ia}$, Eq. 7), meandering rivers with scroll bars ($< \omega_{sc}$), meandering rivers with chute bars ($< \omega_{cb}$, Eq. 3) and rivers with braid
Figure 3: Example of occurrence of chute and dynamic scroll bars in gentle and tight bends of a high energy meandering river with a mixed sand-gravel bed. In tight bends transitional chute/scroll bars may form (after van den Berg and Middelkoop, 2007). Allier River near Bressoles, France (location 117 in online supplementary material). Aerial photograph 9 September 1997, (infrared false colour): Source: Inventaire Forestier National, Lyon, France.
bars (> \(\omega_{bm}\)). Stressing again that the discriminators in this paper are not hard thresholds but indicators of transitions (‘transitionators’), we suggest a new discriminator for meandering rivers with scroll bars and meandering rivers with chute bars (and scroll bars) in between Eq. 3 and Eq. 7:

\[
\omega_{sc} = \frac{900}{\sqrt{10}} D_{50}^{0.42} \approx 285 D_{50}^{0.42}
\]

(8)

where the subscript \(sc\) indicates the discrimination between scrolls and chutes.

2.2. Theoretical prediction of bar pattern

2.2.1. Bar theory of Struiksma et al. (1985)

Bar theory (Struiksma et al., 1985) (also see Seminara and Tubino, 1989) predicts the existence of bars and bar regime, given flow conditions. The theory of Struiksma et al. (1985) is valid for forced alternate bars, where ‘forced’ means that bars are fixed in location to bends or other perturbations in the channel boundary, in contrast to free bars that may migrate. The theory of Struiksma et al. (1985) can also easily be adapted to predict whether multiple bars can exist across the channel, that is, whether it braids. Crosato and Mosselman (2009) derived a predictor for the number of bars from the theory of Struiksma et al. (1985), which is sketched below. Free bar theory gives similar predictions of bar regime (Marra, 2008; Crosato and Mosselman, 2009) (though not of bar dimensions but that is not our objective here) so that we can apply the theory given below to all alluvial rivers.

The Struiksma et al. theory is based on interaction between flow and a deformable sediment bed. The direction of sediment transport may differ from the direction of depth-averaged flow because of gravitational effects on transverse and longitudinal slopes and because of spiral flow in bends. The steady bed topography in river bends can be understood as a combination of a transversely sloped bed depending on the local channel curvature and a pattern of steady alternate bars induced by upstream variations (or perturbations) in channel curvature. Struiksma et al. (1985) identified four characteristic length scales in the linearised equations for the steady alternate bars, namely the adaptation length of flow \(\lambda_w\), the adaptation length of a bed disturbance \(\lambda_s\), the wavelength of the bar \(L_p\) and the damping length of the bar \(L_D\) (Fig. 5).

The adaptation length of flow \(\lambda_w\) (m) is given as:

\[
\lambda_w = \frac{C^2 h_d}{2g}
\]

(9)
Figure 4: Energy-related continuum of bar types in single-thread channel patterns. From high to low streampower: A. Meandering with chute bars. Sheep River at Black Ranch, Alberta, Canada (Kellerhals et al. (1972), location 51 in online supplementary material). B. Meandering with scroll bars. Assiniboine near Portage La Prairie, Manitoba, Canada (Rannie (1990); location 96 in online supplementary material). C. Immobile sinuous channels. Nqoga south of Omdop airstrip, Botswana (Tooth and McCarthy (2004); location 120 in online supplementary material).
Figure 5: Regimes of bars generated at a perturbation for sand-bed rivers (A) and for gravel-bed rivers (B). Most of the difference between sand-bed and gravel-bed rivers is caused by the nonlinearity of sediment transport ($n$). Width-depth ratio is indicated at top of figures. Dashed vertical lines indicate theoretical thresholds of bar regime.
where \( h_a = \) actual (measured) water depth (m) and \( C = \) the Chézy friction coefficient \((\sqrt{\text{m/s}})\), derived from the data as:

\[
C = \frac{u}{\sqrt{RS}}
\]

(10)

where \( u = \) cross-sectionally and depth-averaged flow velocity (m/s), \( S = \) channel gradient and \( R = \) hydraulic radius (m), here calculated as

\[
R = \frac{W_a h_a}{W_a + 2h_a}
\]

(11)

where \( W_a = \) actual (measured) channel width (m). With specification of water depth or velocity, the missing parameter follows from continuity \( Q = uh_a W_a \), where \( Q = \) flow discharge \((\text{m}^3/\text{s})\), choice discussed later).

The adaptation length of a bed disturbance \( \lambda_s \) (m) is calculated as:

\[
\lambda_s = \frac{h}{\pi^2} \left( \frac{W_a}{h_a} \right)^2 f(\theta)
\]

(12)

where the magnitude of the transverse slope effect is calculated from an empirical function (Koch and Flokstra, 1981; Talmon et al., 1995):

\[
f(\theta) = 9 \left( \frac{D_{S0}}{h_a} \right)^{0.3} \sqrt{\theta}
\]

(13)

where \( \theta = \) the nondimensional shear stress (Shields number) defined as

\[
\theta = \frac{\tau}{(\rho_s - \rho) g D_{S0}}
\]

(14)

in which \( \rho \) and \( \rho_s \) are the density \((\text{kg/m}^3)\) of water and sediment, respectively. The shear stress \( \tau \) (Pa) is calculated as:

\[
\tau = \rho gRS
\]

(15)

Often \( f(\theta) = \alpha_\theta \sqrt{\theta} \) is used to describe or numerically model bar regime, dimensions and dynamics, where \( \alpha_\theta \) is used for calibration. This indicates that the transverse slope-related part of the theory is rather uncertain, so that the predictions of the theory are uncertain as well.

Intuitive understanding of these theoretical length scales is offered as follows. Consider a long straight channel with perfectly uniform steady flow which suddenly enters a bend. This bend acts as a perturbation to the flow: as momentum
is conserved, the flow is directed onto the outer bend, forcing the water surface to rise at the outer bank. This additional pressure causes a spiral flow to set up that, near the bed, is directed towards the inner bend. This flow pattern does not appear instantaneously but develops asymptotically towards equilibrium, which is characterised by an adaptation length $\lambda_w$ at which about 63% of the adaptation has been accomplished. In response to the flow pattern the bed deforms through sediment transport. As the near-bed flow is directed slightly towards the inner bend, sediment transport is directed slightly inwards as well and a bar is built up in the inner bend. On the resulting transverse bed slope, gravity opposes the inward movement of sediment to some extent. The bed cannot adapt immediately downstream of the bend (or there would be a ridiculous discontinuity in the bed surface) but adapts asymptotically, characterised by the adaptation length $\lambda_s$.

Nondimensional bar period (or wavelength) $L_p$ (m) is calculated by:

$$\frac{2\pi\lambda_w}{L_p} = \frac{1}{2}\sqrt{(n + 1) \left(\frac{\lambda_w}{\lambda_s}\right)^2 - \left(\frac{n - 3}{2}\right)^2}$$

(16)

where $n$ = the degree of nonlinearity of sediment transport versus depth-averaged flow velocity ($q_b = f(u_n)$). For a classical bed load transport predictor such as Meyer-Peter and Mueller (1948), $n = 3$ for high Shields numbers and increases to infinity towards the critical Shields number for sediment motion. We choose with $n = 4$ for sand-bed rivers and for gravel-bed rivers $n = 10$ (following Crosato and Mosselman, 2009) as gravel is closer to the threshold of motion so that the nonlinearity is stronger (Fig. 5). The effect of this choice will be assessed later.

Nondimensional damping length $L_d$ (m) of the bars is calculated by:

$$\frac{\lambda_w}{L_d} = \frac{1}{2} \left(\frac{\lambda_w}{\lambda_s} - n - 3\right)$$

(17)

The theory predicts whether forced bars dampen out in less than one bar length (overdamped regime) or over longer distance so that multiple bars along the river may exist (underdamped regime) or excite (excitation regime, $L_d < 0$) (Fig. 6). As shown above, this characteristic of bars is a function of the nondimensional Interaction Parameter ($IP$): $IP = \frac{\lambda_s}{\lambda_w}$

(18)

which depends strongly on width-depth ratio and nonlinearity of sediment transport, and weakly on hydraulic roughness and sediment mobility. For narrow and
deep channels the bars are overdamped. For a local perturbation this results in the disappearance of the bar within a short distance downstream of the perturbation. For a bend the transverse slope adapts to the equilibrium transverse slope within a short distance. Overdamping occurs for

\[ IP \leq \frac{2}{n + 1 + 2\sqrt{2n-2}} \]  \hspace{1cm} (19)

For channels of intermediate width-depth ratio the bars are underdamped:

\[ \frac{2}{n + 1 + 2\sqrt{2n-2}} < IP < \frac{2}{n-3} \]  \hspace{1cm} (20)

Underdamping leads to overdeepening of the outer-bend pool and associated enhancement of the bar in the inner bend just downstream of the entrance of the bend or other perturbations (such as sudden widening, narrowing or bank irregularities). For very wide and shallow channels the bars become unstable and theoretically grow in height downstream of the perturbation. This excitation occurs for

\[ IP \geq \frac{2}{n-3} \]  \hspace{1cm} (21)

Intuitively this can be understood as a positive feedback between the flow and the deforming bed. Both flow and bed adapt to the perturbation, but over a different length. If the flow has already adapted to the upstream perturbation whilst the bed has not yet adapted to the same perturbation, then the flow will again adapt to the changing bed, which will cause further adaptation of the deformable bed downstream, and so on. In this condition the bed deformation grows in downstream direction. The resulting bed topography ranges from pronounced finite-amplitude alternating bars to braided channel patterns. For lower \( IP \) the bed deformation dampens out downstream of the perturbation (Mosselman et al., 2006).

The theory presented by Struiksma et al. for mode 1 bars can easily be adapted to higher mode bars (also see Parker, 1976) through:

\[ \lambda_s = \frac{h}{\pi^2} \left( \frac{1}{m} \frac{W_a}{h} \right)^2 f(\theta) \]  \hspace{1cm} (22)

where \( m = \) mode as defined in Fig. 6. For any mode, the threshold between underdamped and excited is found at:

\[ IP_{ue} = \frac{2m^2}{n-3} \]  \hspace{1cm} (23)
Figure 6: Definition of bar regime and bar mode (after Parker, 1976; Struiksma et al., 1985; Mosselman et al., 2006; Crosato and Mosselman, 2009).
A river is predicted to braid if the actual $IP$ for higher modes is above this threshold.

The range of width-depth ratios where underdamped bars form is mostly determined by the nonlinearity of sediment transport $n$. Figure 5 shows that this range is much narrower for gravel-bed rivers than for sand-bed rivers. For width-depth ratios of 50 and higher the bar regime in gravel-bed rivers is excitation, and underdamped for mode 5 ($B_i = 3$). We can now hypothesise that braided rivers are more numerous in gravel than in sand if we assume that width-depth ratio is independent of bed particle size.

2.2.2. Bar mode theory of Crosato and Mosselman (2009)

Crosato and Mosselman (2009) derived a mode predictor from the theory of Struiksma et al. (1985), which compared favourably with observed modes in a number of braided rivers in sand and gravel:

$$m^2 = \frac{0.17g(n-3)W^3S}{\sqrt{\frac{\rho_c-\rho}{\rho}D_{50}CQ}}$$

(24)

where the relation between mode $m$ and braiding index $B_i$ is defined as

$$B_i \equiv \frac{m-1}{2} + 1$$

(25)

Herein, a river is considered single-thread for $B_i \leq 1.2$, moderately braided for $1.2 < B_i < 3$ or braided for $B_i \geq 3$, where $B_i =$ number of active channels across the river width $W_a$ during channel-forming discharge (Fig. 6) (Egozi and Ashmore, 2008).

The threshold from underdamped to excited bars (for a given mode) is here interpreted as the transition to dominant presence of these bars in reality. These thresholds are mathematically identified as hard thresholds, but in practice merely give reference values in the continuum from overdamped to underdamped to excited bars (Fig. 5). The theory is strictly valid for forced bars so that underdamped forced bars of mode 1 are equivalent to alternate bars or scroll bars in meander bends where the bend provides the forcing. If theory predicts $1.2 < B_i < 3$ then this is interpreted as chute cutoffs or weakly braided.

It is important to realise that the physics-based method does not provide a predictor of river patterns, because it requires knowledge of the actual channel width, depth and channel gradient. These variables are strongly coupled to the river pattern itself through the feedback between bar pattern, bank erosion and style of
floodplain formation. However, it provides a physics-based partial explanation for the empirical method.

3. Data collection and analysis

3.1. Selection of equilibrium rivers

The present analysis refers to natural rivers in unconfined alluvium that are in dynamic equilibrium condition over a length scale of a few tens of meander lengths (hundreds of widths). The selection criteria of rivers were the same as in van den Berg (1995):

- \( Q > 10 \text{ m}^3/\text{s} \)
- perennial flow regime
- no valley constraints
- no dams, jetties, groynes, sills, bank protection
- no artificial cutoffs
- no roads or rural areas bordering on the channel
- no clear bed degradation (e.g. no clear terraces)
- no sign of strong discharge wave modification (e.g. bars overgrown with forest or clearly underfit patterns such as presence of small-wavelength meanders in long bends)

These are all related to unwanted effects on the width of the channels as this would affect the bar and channel pattern and their natural dynamics. We stress that the criteria for river selection and classification outlined above were strictly followed irrespective of their potential specific streampower, which was calculated only after selection.

Based on Google Earth images (accessed February-July 2009) we classified observed rivers by active braiding index, presence of scroll bars, chute bars and scrolled pointbars. Single-thread river patterns were subdivided in meandering with chute bars, meandering with scroll bars and stable straight or sinuous rivers (Fig. 4). We characterised braiding intensity by the braiding index, defined as the average cross-sectional number of active, unvegetated or barely vegetated braids \((B_i)\), which gives the best combination of rapid measurement and precision for
Google Earth (Egozi and Ashmore, 2008). We counted active braids visually using indications such as trees falling over into the channel in outer bends, unvegetated higher parts of pointbars and administrative borders that no longer follow the river. In multi-thread systems highly braided and moderately braided were distinguished above and below $B_i = 3$. To minimise interpretation differences this visual classification was done by only one operator (JHvdB). The data and geographical coordinates are provided in the online supplementary information.

The van den Berg data were revisited and 74 out of 143 rivers were removed. In most cases the reason for removal was an obviously underfit river pattern. Information gathered from various sources for most cases revealed that this resulted from various man-induced causes, such as water extraction or dam building. Most removed cases were straight rivers with a sinuosity $P < 1.3$. The cause of the straight channel pattern usually was a narrow valley, either by being confined between rocks or by incision of the river. van den Berg (1995) found that straight rivers were not classified well but occurred in both the meandering and braided fields of the diagram. The reanalysis now explains this: those straight rivers did not meet the criteria. Their stable occurrence is typical for moderately entrenched or valley-confined rivers of moderate flow energy as described by Nanson and Croke (1992) and Rosgen (1994). In an unconfined setting these rivers would have developed meandering or braiding patterns. Our focus on alluvial rivers without bed degradation also led to exclusion of the incising rivers used by Bledsoe and Watson (2001). Many of the rivers selected by Crosato and Mosselman (2009) may have been suitable to test bar pattern but were unsuitable for our purpose of river pattern analysis as they did not meet our criteria.

3.2. Collection of new data and analysis

A literature survey resulted in an extension of the remaining data of van den Berg of 69 rivers to a total of 127 rivers. Required variables were mean annual flood discharge ($Q_{af}$) and bankfull discharge ($Q_{bf}$), median particle size ($D_{50}$) of the channel bed, valley slope ($S_v$) or sinuosity ($P$) and channel slope ($S$, where by definition $P = S/S_v$). Data of actual width ($W_a$), depth ($h$) and velocity ($u$) during conditions with bankfull discharge $Q_{bf}$ or mean annual flood discharge $Q_{af}$ were collected as far as available. Data was converted to SI where necessary. The data are presented as online supplementary material. A summary of the data is shown as probability density distributions for several variables in Fig. 7. This shows a lognormal distribution of most variables, except particle size and the related Shields number, which is explained by the well-known sparsity of rivers with pea gravel (2–8 mm) as bed sediment.
Figure 7: Probability density of variables representing the dataset.
Mean annual flood discharge was used as effective channel-forming discharge. Reported bankfull discharge was used instead if mean annual flood discharge was not found in the literature. This choice was made for several reasons. Mean annual flood is less dependent on channel pattern than bankfull discharge. Furthermore, bankfull discharge reported in literature is less reliable, as there are a large number of definitions (Williams, 1978) and in the data sources generally it is not clear what definition was used. Formative discharge can also be defined as the discharge at which on average the same annual bed sediment load is transported as by the full probability distribution of discharge. In fact this also is not a completely pattern-independent measure of discharge, as it is influenced by the width and depth of the channel. The maximum of average annual bed material load commonly coincides with the water level at which the flow resistance per unit of discharge is minimal, which is the bankfull level. As a consequence the formative discharge changes if the width or depth of the channel is changed. The dimensions of the channel also determine how a flood wave is transformed in downstream direction, so that downstream discharge is not independent from channel characteristics. Yet the least pattern-dependent formative discharge measure is a frequency-based hydrological variable: the mean annual flood discharge.

The discriminators \( B_i = 1.2 \) and \( B_i = 3 \) as well as Eq. 23 for these values of \( B_i \) were compared to the data by calculating Eqs. 18 and 25 for all rivers where a depth or velocity was available. The predictive capacity of the bar pattern from theory was then compared to the empirical discriminators for specific potential valley streampower.

To assess the nonlinearity of sediment transport, we also plot the criteria for bedload and suspension (Soulsby, 1997). These must be converted from nondimensional shear stress (Shields number) to streampower. From their definitions and the law of Chézy, it can be derived that:

\[
\omega = \frac{\tau^{1.5}C}{\sqrt{\rho g}} = \theta^{1.5}C\left[\frac{\rho_s - \rho gD_{50}}{\sqrt{\rho g}}\right]^{1.5}
\]

For our dataset the average Chézy number is 28 and the data confirm no correlation between Chézy number and water depth or bed sediment size. Typically, \( \rho_s = 2650 \text{ kg/m}^3 \), \( \rho = 1000 \text{ kg/m}^3 \) and \( g = 9.81 \text{ m/s}^2 \) so that \( \omega \approx 0.283 \tau^{1.5} \).

3.3. Inapplicability of the prediction methods to anabranching, anastomosis and wandering rivers

The anabranching river pattern often is added as a separate category or higher level to channel pattern classifications (Schumm, 1968; Rust, 1978; Alabyan and
Chalov, 1998; Latrubesse, 2008) (Fig. 1). It is defined as a system of multiple channels characterised by vegetated or otherwise stable alluvial islands (floodplain) that divide flows at discharges up to nearly bankfull (Nanson and Knighton, 1996). Here we argue that the higher-level multi-thread property is unrelated to streampower.

Anastomosing rivers are anabranching systems with low streampower insufficient for significant channel mobility so that individual channels may be straight or sinuous but not meandering (Makaske et al., 2002). A likely explanation of anastomosis is that it is caused by avulsion driven by upstream sediment overloading (Abbado et al., 2005). More precisely, the aggradation of the floodplain and levees are exceeded by the aggradation of the channel bed. The bed sediment cannot be accommodated in extending pointbars because the river is not strong enough to erode banks. Hence the river is forced to avulse by channel aggradation (Makaske et al., 2009). This strongly suggests that the anastomosing river pattern is a disequilibrium pattern which is outside the scope of this paper.

Some 40 years ago wandering rivers were added to the classical meandering-braided continuum (Neill, 1973; Church and Rood, 1983). They are sometimes called island-braided (e.g. Ward et al., 2002). The wandering river pattern has a complicated channel planform with long sections exhibiting multiple channel anabranches surrounding semi-permanent islands supporting mature forests, separated by single channel sections. Church and Jones (1982) suggested that incidental large sediment input from tributaries might have caused shoaling of thalweg areas that would have triggered avulsion and the formation of anabranching river sections. Burge and Lapointe (2005) demonstrated that avulsions that create new anabranches in many cases are forced by beaver dams or ice jams. Ward et al. (1999) propose that wandering systems may evolve from coagulating tail bars generated in the wake of large woody debris. Wandering patterns may also be created when the effective discharge reduces, for instance due to of the construction of storage reservoirs. As a result braid bars may become stable, covered by dense vegetation and coalesce by the siltation of smaller braid channels. Examples of such systems misclassified as ‘wandering’ are indicative of a future transition to meandering (as probably happened in the Allier River, as indicated on historical maps in the local archives). Thus, wandering is the result of either an unusual non-fluvial forcing mechanism or disequilibrium. Such mechanisms are not included in the river pattern prediction method presented here. Also, the prediction method refers to single channel systems. Therefore we do not present wandering rivers as a separate river pattern. However, it has been made clear that without such external forcing mechanisms wandering rivers would be braided or meandering near
the meandering-highly braided discriminant (Nanson and Knighton, 1996; Burge and Lapointe, 2005).

Anabranching is common in the largest rivers of the world with \( Q_{bf} > 17,000 \text{ m}^3/\text{s} \), such as the lower Brahmaputra, the Congo and the Amazon. Latrubesse (2008) suggested that these systems plot in a very restricted area of Fig. 8, with stream-power values \( 3 < \omega_{pv} < 25 \text{ W/m}^2 \) and grain sizes \( 0.1 < D_{50} < 0.5 \text{ mm} \). There are exceptions to this rule, however, such as the Brahmaputra at Dibrugarh, Assam, India, with \( Q_{bf} = 40,000 \text{ m}^3/\text{s} \) (Chitale, 1970; location 19 in online supplementary material), which has a highly braided pattern and plots accordingly in the stability diagram. Another hypothesis for the anabranching of the largest rivers is superposition of a bankfull discharge-related pattern on a large-scale flood-related pattern (Alabyan and Chalov, 1998). For instance, the Brahmaputra/Jamuna river shows intricate anabranching or braiding during low flow, but a mode 2 \( (B_i \approx 1.5) \) river during a high monsoon flood (Thorne et al., 1993). We can speculate that large floods in these large rivers are strong enough to overcome floodplain sediment and vegetation strength so that the floods deform floodplains as if they were channels, but this is beyond the scope of this paper. We conclude that the existence of rivers with multiple channels is not clearly empirically or theoretically related to streampower.

4. Results

4.1. Empirical prediction of bar and channel pattern

Four stability fields can be distinguished in the new empirical diagram: rivers with stable channels, meandering rivers with scroll bars, meandering rivers with scroll and chute bars as well as moderately braided rivers, and finally braided rivers (Fig. 8). Moderately braided rivers and meandering rivers with chute bars plot within the same field (Fig. 8). This is not a surprise, as a small increase of channel-gradient related streampower may increase the activity of chutes in meandering rivers causing chute cutoffs which change the river pattern to moderately braided (see discussion). Note that if actual streampower based on actual channel slope and measured water depth were used then the channel patterns would not be separated at all.

The discriminators indicate which pattern occurs above the line, but do not indicate that a lower-energy pattern does no longer occur above this line. For example, scroll bars occur at \( \omega_{pv} \geq \omega_{ia} \) (Eq. 7), whilst rivers without bars may also occur in this field. Likewise, braided rivers occur for \( \omega_{pv} \geq \omega_{bm} \) (Eq. 3) but hardly below this discriminator, whilst some chutes and moderately braided
Figure 8: Patterns of equilibrium alluvial rivers plotted with the potential specific streampower related to valley gradient and predicted width. A. Data subdivided by bar pattern and B. Data subdivided by sinuosity. Eq. 3 (top) is upper limit of meandering and lower limit of highly braided. Eq. 8 (middle) is lower limit of meandering with chute bars or moderately braided. Eq. 7 (bottom) is lower limit of meandering with scroll bars. Dotted lines are approximate criteria for beginning of motion and beginning of suspension. The lower discriminators are a factor of $\sqrt{10}$ and 10 lower.
Table 1: Classification of channel pattern by potential specific streampower.

<table>
<thead>
<tr>
<th>class</th>
<th>correctly classified</th>
<th>incorrectly classified</th>
</tr>
</thead>
<tbody>
<tr>
<td>no bars $\omega_{pv} &lt; \omega_{ia}$</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>scroll bars $\omega_{pv} \geq \omega_{ia}$</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>chutes $\omega_{pv} \geq \omega_{sc}$</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>moderately braided $\omega_{pv} \geq \omega_{sc}$</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>braided $\omega_{pv} \geq \omega_{bm}$</td>
<td>20</td>
<td>2</td>
</tr>
</tbody>
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rivers plot both above and below this same discriminator. The present discriminators are here reinterpreted as lower thresholds rather than discriminators, but it is again stressed that these lines represent an estimate of probability of existence—not a hard threshold. Table 1 indicates that most rivers correctly plot above the applicable threshold.

The original discriminator between meandering and braiding (Eq. 3) must be reinterpreted. This line was thought to represent the 50% probability line separating stability fields of dominantly braiding or meandering (Bledsoe and Watson, 2001). The present distinction between moderately braided ($B_i < 3$) and braided ($B_i \geq 3$) rivers revealed that only braided rivers plot above the discriminator. Furthermore, only very few meandering rivers of the new dataset are located above the discriminator (Fig. 8) which invalidates the 50% interpretation. Therefore, Eq. 3 is reinterpreted as a lower ‘threshold’ for highly braided systems.

Inactive channels are not necessarily straight. For example, the highly sinuous Barwon river (near Walgett, Australia, location 113 in online supplementary material) has no significant bank erosion and lateral migration. Classifying this river as meandering based on sinuosity would contradict the low streampower value previously associated with straight rivers (Leopold and Wolman, 1957), whereas classifying this river as single-thread river devoid of any scroll bars and without significant bank erosion agrees with the low streampower value associated here to immobility (Makaske et al., 2002). Thus immobile sinuous channels may seem to meander at first sight, but this is merely a relic or is caused by antecedent relief.

Vegetation significantly affects channel mobility in a similar way as engineering structures, hardrock and strong clay layers on the point bar. Several meandering rivers with scroll bars, but without chutes and chute bars, plot near or even slightly above the meandering stability field. These examples refer to tortuously meandering systems in the Brazilian tropical forest, such as the Jurua (locations 58 and 59 in online dataset). The high sinuosity of these rivers is caused by the dense vegetation on the pointbar that resists cutoff by chuting (Baker, 1978). This
suggest that a clearing of the forest for some of these cases might result in a change of channel pattern into less tortuous meandering system with chute bars, or—in view of the high potential energy values—even into a moderately braided system. Immobile channels may occur at relatively high streampower values in case that roots of the bank vegetation reach below the channels floor. Channels with $Q < 15 \text{ m}^3/\text{s}$ in a forested area were also immobile for this reason (Beechie et al., 2006).

Lines indicating the threshold of motion and of suspension (Kleinhans, 2005) show that gravel-bed rivers generally occur close to the threshold of motion whereas sand-bed rivers are dominated by suspension. This confirms that the chosen degree of nonlinearity $n$ of sediment transport versus depth-averaged flow velocity should indeed be higher for the gravel-bed rivers ($n = 10$) than for the sand-bed rivers ($n = 4$) for sand-bed rivers in agreement with (Crosato and Mosselman, 2009). Note that this remains a simplification as the sediment of gravel-bed rivers is commonly much more poorly sorted than of sand-bed rivers, so that the beginning of motion will be more gradual and the mode of sediment transport mixed bed load and suspended load.

As a test whether the original discriminant (Eq. 3 is still valid for the present dataset we recalculated the power by ordinary least square fitting of a power function through potential specific streampower versus particle size for the rivers with scroll bars, chute bars and moderately braiding. The power was 0.41, close to the original 0.42, which we take as corroboration. This is further supported by Bledsoe and Watson (2001) who found the same power. We compared the streampower and mobility number approaches of van den Berg (1995) and Bledsoe and Watson (2001) but no difference in classification was found as expected.

4.2. Theoretical prediction of bar pattern compared to empirical prediction

Here we compare theoretical and empirical predictions of bar pattern. To represent the position of rivers relative to the empirical discriminators on one axis (Fig. 9), the trend of increasing streampower with particle size is removed by normalising streampower of rivers by the braiding discriminator as $\omega_{pv} \geq \omega_{bm}$.

The mode is straightforwardly interpreted as active Braiding Index. Braided rivers are reasonably separated at $B_i = 3$ from moderately braided rivers or meandering rivers with chute cutoffs (Fig. 9A). The latter predict many meandering rivers to be braided or moderately braided or to have chute bars that they do not have. Table 2 indicates that most multi-thread rivers are correctly classified, but that single-thread rivers occur up to $B_i \approx 4$. This agrees with the finding that
Figure 9: Comparison of empirical and theoretical predictions for bar pattern, and, by implication, for channel pattern. Streampower is normalised with the braided-meandering discriminator (Eq. 3). Same legend as Fig. 8a. A. Comparison of streampower-based prediction and theoretically predicted bar mode (Eq. 24), here expressed as Active Braiding Index. B. Comparison of empirical predictions and theoretical bar regime (Eq. 23) for gravel-bed rivers. C. Same as B, for sand-bed rivers.
Table 2: Classification of channel pattern by theoretical braiding index $B_i$.

<table>
<thead>
<tr>
<th>class</th>
<th>correctly classified</th>
<th>incorrectly classified</th>
</tr>
</thead>
<tbody>
<tr>
<td>single-thread (no bars, scroll bars) $B_i \leq 1.2$</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>chutes and mod. braided $1.2 &lt; B_i \leq 3$</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>braided $B_i &gt; 3$</td>
<td>9</td>
<td>0</td>
</tr>
</tbody>
</table>

rivers with scroll bars and chute bars overlap in the empirical streampower-based diagram.

If the Interaction Parameter is considered, four bar regimes are distinguished by three theoretical thresholds (Fig. 9B,C). The first is the transition from overdamped to underdamped bars, indicative of the emergence of bars in very narrow and deep channels. The second is the transition from underdamped bars to excited bars of $B_i = 1$, indicative of pronounced scroll bar formation. The third is the transition to excited bars of $B_i = 3$, indicative of braiding. For gravel-bed rivers, many meandering rivers with chute bars are theoretically predicted to braid weakly. We consider this correct as the number of parallel active channels is larger than unity. For sand-bed rivers, many channels without bars are indeed predicted to be overdamped, but many rivers with chute bars are predicted in the underdamped regime, which we do not consider correct.

Observations are in agreement with the prediction from theory that braided rivers are more numerous in gravel than in sand because the range of width-depth ratios where alternate or low mode bars occur is narrower for higher nonlinearity of sediment transport ($n$) (see Fig. 8A and 9B,C).

In short, the theory shows the same trends as the empirical predictors. Theory is less accurate. Although part of this may be attributed to the fact that the empirical predictors were based on the dataset, this result is surprising, as the results of theoretical predictions are heavily sustained by the use of actual measured channel widths of the channel patterns that are predicted by the theory.

5. Discussion

5.1. Channel width prediction and channel pattern

The empirical method has been criticised by Lewin and Brewer (2001, 2003) for its use of a regime based estimate of channel width rather than actual width, because this results in incorrect values of the potential maximum of available energy. Although the criticism is valid it is beside the mark, as the computation of channel width aims at a pattern-independent reference value for channel pattern,
and precisely for this reason intends not to predict actual width which is pattern-dependent (van den Berg, 1995).

To demonstrate the effect of the used predictor for channel width we plot predicted against measured width (Fig. 10). Channel widths were predicted with Eq. 2 and with the channel width predictor of Parker et al. (2007). Both were found to underpredict the width of many braided rivers in our dataset and overpredict that of many meandering rivers. Parker et al. (2007) also predicts channel depth. Although much scattered, it overpredicts depth of many braided rivers and underpredicts depth in meandering rivers. Thus the Parker et al. predictors yield underpredicted width-depth ratios for rivers that braid and overpredicted width-depth ratios for rivers that meander. Only width predictors with a power larger than 0.5 and information on the strength on the banks for the multiplication coefficient would have predicted the widths correctly, but then the prediction would no longer be independent.

The empirical channel pattern predicts the patterns well precisely because the width is incorrectly predicted. This can be understood as follows. If actual width were used then the streampower decreases for rivers where width was overpredicted, and increases for rivers where width was underpredicted so that the discriminative power is entirely lost. Or, in other words, by using the pattern-independent width predictor the streampower for rivers with high width-depth ratios is overpredicted. If streampower were that large in reality because the river were too narrow and deep, then the excess energy would likely be spent on channel enlargement, in which case the width-depth ratio would increase to the actual value. The reverse would be the case for rivers where streampower is underpredicted.

Bar theory, on the other hand, requires the actual observed channel widths and channel gradient for good prediction. For prediction of width, the nature of the banks must be known. A river with a large supply of overbank fines and/or abundant vegetation will develop stronger banks that are more difficult to erode. As a result the channels will be narrower, deeper, and tend to other bar regimes than in the case of entirely noncohesive sediments. This means that independent prediction of bar pattern requires a good predictor for width that includes effects such as floodplain strength and vegetation and a predictor of sinuosity (see Klein-hans, 2010, for review). This is problematic as the bank erosion process depends strongly on pattern.

Finally, we note that the effect of using different width predictors for sand-bed and gravel-bed rivers is small. The empirical channel pattern discriminators (Fig. 8) were recalculated (not shown) using the predictor for reference width
Figure 10: Effect of hydraulic geometry on channel pattern. All data are shown. A. Width prediction according to Eq. 2 as in van den Berg (1995). B. Width prediction with the Parker et al. (2007) predictor for gravel bed rivers. C. Depth prediction using Parker et al. (2007).
(Eq. 2) with an average coefficient $\alpha = 4.0$ rather than two different ones for sand bed rivers and gravel bed rivers. The effect was limited to a slight rotation of the data on the centre of the graph in agreement with the findings by Bledsoe and Watson (2001). The power on diameter would change from 0.42 to 0.33 approximately.

5.2. Sinuosity and streampower

Meandering patterns have been subdivided in the past by sinuosity $P$ (Schumm, 1963; Rust, 1978). It is a common perception that sinuosity tends to increase in response to a steepened valley gradient and vice versa (e.g. Ackers and Charlton, 1970), because energy gradient is adapting to an equilibrium between flow transporting capacity and sediment supply. Evidence for this was found in a number of case studies of alluvial rivers in plains subject to active tectonic movements (Schumm, 1969; Burnett and Schumm, 1983; Schumm et al., 2000). At first sight this might suggest that tortuous meandering rivers in general would represent relative high energy conditions.

Yet, other factors influence sinuosity. Vegetation (Baker, 1978), the percentage silt-clay in the bank material (Schumm, 1963) and channel bed grainsize (Rosgen, 1994; Dade, 2000) may all obscure or even counter valley gradient-related trends found elsewhere. For instance, in river channels of the Okavango wetlands, Botswana, which is also an area with differential tectonic movements, sinuosity decreases with increasing valley gradient (Tooth and McCarthy, 2004). Also on intertidal mud flats the sinuosity decreases with increasing gradient (Kleinhans et al., 2009). As the size distribution and quantity of sediment supplied to a river is different for each case, the mentioned equilibrium energy slope is different for each river. Therefore, specific downstream relations between sinuosity and valley slope found in a number of river plains cannot be generalised. Our dataset support this statement (Fig. 11A). Rosgen (1994) and Dade (2000) showed a clear inverse relation between channel slope and sinuosity, which might suggest a similar relation between streampower and sinuosity. Our data shows, in contrast, that such a relation does not exist (Fig. 11B). This corroborates that the inverse relation of channel slope with sinuosity is a consequence of sinuosity, not a cause.

Moreover $P$ for a given reach of a river does not take a characteristic, stable value but typically shows important fluctuation in time and space. Very large changes in $P$ may be caused by series of meander cutoffs that often cluster in time due to events such as large floods, vegetation mortality in cold spells, and human interference. For instance, $P$ fluctuated between 1.40 and 2.92 in a reach of the River Bolin, UK, over a time period of 162 years (Hooke, 2004). In the Allier,
Figure 11: A. Lack of correlation between valley slope $S_v$ and sinuosity $P$. B. Lack of correlation between relative potential streampower $\omega_{pv}/\omega_{cb}$ and sinuosity $P$. 
France, a cascade of chute-cut offs triggered by the construction of a bridge and a large flood resulted in a temporary reduction of the sinuosity from 1.53 to 1.13 and an increase of braiding index (Fig. 12). The rapid recovery to $P = 1.4$ after this event illustrates that rate of change of sinuosity is strongly related to the velocity of channel migration and thus with flow energy. But a flow energy relation with sinuosity is not obvious from the data. This disposes the use of sinuosity based classifications for meandering pattern prediction.

6. Conclusion: a bird's eye view on river channel patterns

Bar and channel patterns can well be discriminated and predicted with channel particle size and specific potential streampower calculated from mean annual flood discharge, valley gradient and width predicted with a hydraulic geometry relation. Empirical power functions of channel particle size are given as lower thresholds for meandering rivers with scroll bars, for meandering rivers with chutes or weakly braided rivers, and for braided rivers.

Bar pattern is reasonably well-predicted by forced-bar theory, particularly the transition from single-thread (straight and meandering) to multi-thread (chute-cutoffs and braided). Bar theory demonstrates the importance of actual channel width-depth ratio and channel gradient. These are, however, strongly pattern-dependent so that bar theory is incomplete as an independent predictor of channel and bar pattern. Rather, bar theory explains why the deliberate misprediction of channel width for the empirical pattern prediction is required for the predictive success of the latter.

Similar channel and bar patterns emerge along the entire particle size range from fine sand-bed to cobble rivers. The range of specific potential streampower where meandering patterns occur is narrower in gravel than in sand. The difference arises from the higher nonlinearity of sediment transport in the bed load-dominated regime, for which bar theory predicts a narrower range of width-depth ratios where meandering may occur.

Anabranching of rivers is unrelated to streampower but is related to additional factors such as river confinement, bank and floodplain strength, degradation or aggradation and avulsion. The empirical prediction of pattern is applicable to the individual branches.

7. Acknowledgements

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Figure 12: Aerial photographs of the Allier River near Bressoles, France (location 117 in online supplementary material). In 1980 several bends were cut off by chutes, temporarily reducing sinuosity and transforming the river to weakly braided. Flow is to the north. Rectangle indicates position of Fig. 3. Source: Institut Géographique National, Paris, France.
dra Crosato is cordially acknowledged. Comments on an earlier draft and discussion by Wout van Dijk, Wietse van de Lageweg and Filip Schuurman greatly helped to improve the paper. Margot Stoete of Geomedia is thanked for drawing Fig. 1. The authors contributed in the following proportions to conception and design, data collection, analysis and conclusions, and manuscript preparation: MGK(50,10,60,80%) and RJB(50,90,40,20%). Online Supplementary Information contains the dataset including coordinates for use in Google Earth.

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