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A new empirical river pattern discriminant method based on flow resistance characteristics

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ABSTRACT

A new empirical river pattern classification system is established based on the generalization of the famous Darcy–Weisbach equation. A parameter representing river shape is derived and defined as the river pattern discriminant criteria. After transformation, a couple of discriminant thresholds are determined and expressed as dimensionless forms relating the resistance factor to the relative roughness factor of the channel, which reflect the integrative effects of channel slope, sediment size, bank strength and channel geometry. A threshold function is used to separate single-thread channels (including straight and meandering) from multi-thread channels, and another one is employed to distinguish stable and unstable multi-thread channels (i.e., anabranching and braided) in this paper. A novel bank strength impact factor (μ) is proposed and turns out to be rather representative. Some channel patterns are reasonably redefined using this method. Analysis of various data sets reveals that riparian vegetation condition is a sensitive part of this classification system, in particular for single-thread channels, but not braided channels, because an overlarge width–depth ratio (W/d) could strongly weaken this impact. The definition of anabranching and braided channels herein is actually consistent with the traditional braided channels to some extent. It is also trustworthy that transient anabranching or braiding pattern could occur in a single-thread typical zone following external disturbance, but would eventually return to dynamic equilibrium state. Despite some potential limitations in the construction mechanism, the proposed discriminant method is supported by the selected existing datasets and could effectively distinguish three distinct types of channels by just a few river hydraulic parameters.

1. Introduction

River pattern reveals the physical geometry and dynamic behavioral process of river system (Nanson and Knighton, 1996; Schumm, 1985). It is well understood that an alluvial channel could adjust itself to the ever-changing water flow and sediment conditions. During this process the river pattern could exhibit a series of continuous variations, described as straight, meandering and braided patterns in tradition (Leopold and Wolman, 1957). It is pretty necessary to distinguish several distinct types of channels for better understanding of the consistent changing progresses of river channels in different environment conditions. Numerous classification schemes using discriminant functions have been proposed based on a set of typical properties, such as discharge, channel slope, width–depth ratio, and sediment grain size. Noteworthy is that the still least well-known multi-thread river pattern, anabranching, which is defined as a section of a river that diverts from the main channel of the watercourse and rejoins the main stem downstream (North et al., 2007), has been attracting considerable attention (e.g., Burge, 2006; Eaton et al., 2010; Kleinhans and van den Berg, 2011; Nanson and Knighton, 1996; Schumm, 1981, 1985; Tooth and Nanson, 1999). After intense discussions on the mechanisms of formation and continued existence, anabranching is considered as an equilibrium channel form (Wende and Nanson, 1998) and it does make great contribution to the diversity of river systems. Since it is so, in view of the necessity of including anabranching, basing on tradition, following the popular discriminant mode and developing a novel river pattern discriminant method comprise the focus of this paper, and lead to the capture of different channel patterns. In particular, as a transition between meandering and braided, this “anabranching” is closer to the relatively coarse-grained high energy rivers (Nanson and Knighton, 1996), rather than anastomosing (Gibling et al., 1998; Smith, 1986).

Many early empirical attempts used Leopold and Wolman (1957)'s method as a base model, to improve understanding of the quantitative process of rive pattern transformation. Most of them who focused on the critical discharge to construct discriminant function, later also included critical channel slope and bed grain size (Henderson, 1963; Millar, 2000). For a given bankfull discharge, braided usually corresponds to increased slope, which in turn usually results in stronger

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sand transport rate, increased bank erosion and coarser bed surface sediment (Eaton et al., 2010). Considering that these early methods have some limitations (Nanson and Knighton, 1996), many new threshold schemes appear successively, among which critical specific stream power (Lewin and Brewer, 2001; Petit et al., 2005; Van den Berg, 1995) is outstanding. It can be viewed as a potential status with maximum flow energy and minimum sinuosity condition (Van den Berg, 1995). The classification between braided and meandering channels in unconfined alluvial floodplains is well acceptable. Meanwhile, Lewin and Brewer (2001) argued that the classification of river pattern should not be limited to obtain an all-sided discriminant method, but the thresholds integrated with patterning process domain. Petit et al. (2005) conducted experiments on different sized rivers and concluded that critical specific stream power is the smallest for the largest rivers, while turns to the higher value in intermediate rivers, then becomes the highest in head water streams. The reasons are down to the bedform's larger resistance that consumes energy for bedload transport. Recently, Kleinhans (2010) emphasized that channel pattern is directly bound up with the presence of bars. Then, Kleinhans and van den Berg (2011) combined the empirical stream power-based discrimination method and a physics-based bar pattern prediction method to undertake bold exploration about the underlying reasons of different river channel patterns. It was found that the range of specific potential stream power is rather narrow in gravel-bed meandering channel due to non-linearity of sediment transport; anabranching channel is irrelevant to stream power but subject to additional factors such as bank strength, lateral confinement, avulsion, and vertical morphodynamics change; river pattern can actually be defined by bar pattern, channel division number, and bifurcation condition.

The common features in empirical methods are that more is based on statistical correlation derivation, less to clearly expound inherent processes for discriminating river pattern. These models may really be questioned about application to broader scope, due to original data restrictions. Given the shortcomings, many researchers have been contributing to developing physically based theories, and exploring the relationship variables controlling river evolution process and pattern. Nowadays, particular attention has been given to the combination of leading rational regime theory (Eaton et al., 2004; Kaless et al., 2014) with linear stability models (Fredsøe, 1978; Parker, 1976), which means that morphodynamic condition and fluvial system stability are together considered to describe pattern transition process. When combined with a morphodynamic equation describing the meandering/braiding transition from a linear stability model, regime theories can be used to predict changes in channel pattern in terms of the relevant governing conditions. Many recent regime models that explicitly consider bank stability hold the similar idea (Eaton and Church, 2004; Millar and Quick, 1998).

In this paper, we attempt to develop a physical based classification system, just like Eaton et al. (2010). A threshold could be used to distinguish single-thread and stable multi-thread channels, and another one could be used to distinguish stable and unstable multi-thread channels, from a stability perspective. However, when rereading the original work by Eaton et al. (2010), some limitations of subjectivity become clear that a threshold value of $W/d = 50$ originally recommended for discriminating braided channels was employed to derive bifurcation criteria, and the number of channel divisions exceeding four was subjectively assumed as the beginning of system instability. We hold that this treatment should be regarded warily due to lack of absolute objective stability or instability criterion in fact.

We turn in another new way. The famous Darcy–Weisbach equation (Darcy, 1857; Weisbach, 1848) is generalized from artificial rectangular channel case to natural alluvial channel and expressed as functions of a series of river characteristic parameters, especially including a river pattern parameter. Based on some technical means including scatter diagram analysis, data fitting, appropriate assumptions and so on, we establish a couple of new dimensionless style thresholds for distinguishing different river patterns.

2. River pattern discriminant functions

The Darcy–Weisbach equation is a well-established formula in hydraulics. It was gained through dimensional analysis and was originally developed for analyzing pressure pipe flow. With the development of the theory, in fact, this formula has been generally used in many flow systems, in particular, open channel flow. It has received much acceptance due to the advantage that simulates the relationship between channel roughness, channel geometry, material and velocity (Brown, 2002; Myers and Brennan, 1990). The familiar form of the equation is as follows, relating the head loss, with friction along a specified length of open-channel to the average velocity of the free surface flow:

$$h_f = \lambda \frac{l}{4R} \frac{v^2}{2g} \tag{1}$$

where

h_f is the head loss due to friction (m);
l is the length of the given open-channel (m);
R is the hydraulic radius of the open-channel (m);
v is the average velocity of the free surface flow (m/s);
g is the local acceleration of gravity (m/s^2);
λ is the dimensionless coefficient called the resistance factor.

Make the following reformulation:

$$S^* = \frac{h_f}{l} \qquad v = \frac{Q}{\omega} \tag{2}$$

where

Q is the average discharge of the open-channel;
ω is the wetted cross-sectional area of the open-channel;
S^* is a dimensionless parameter, equal to the channel slope.

Substitute Eq. (2) into Eq. (1), we have:

$$S^* = \frac{h_f}{l} = \lambda \left(\frac{Q}{\omega \sqrt{8gR}} \right)^2 = \lambda Q^{*2} \tag{3}$$

then

$$\lambda = \frac{S^*}{Q^{*2}} \tag{4}$$

where Q^* is a dimensionless discharge, is given by:

$$Q^* = \frac{Q}{\omega \sqrt{8gR}}. \tag{5}$$

According to Nikuradse (1933), in the above formulas, λ can be expressed by:

$$\lambda = f\left(\mathrm{Re}, \frac{R}{\Delta} \right) \tag{6}$$

where

Re stands for the Reynolds number of the channel flow;
Δ stands for the absolute roughness factor of the channel;
R/Δ stands for the relative roughness factor of the channel;
f stands for the function of Re and R/Δ related to resistance factor λ.

For very large Reynolds number, the resistance factor λ is independent of the Reynolds number; it is only the function of the roughness factor R/Δ (Nikuradse, 1933). Zegzhda (1938) conducted experiments