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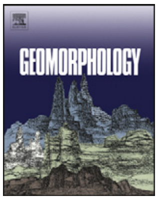

Controls of channel morphology and sediment concentration on flow resistance in a large sand-bed river: A case study of the lower Yellow River

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ABSTRACT

Accurate estimation of flow resistance is crucial for flood routing, flow discharge and velocity estimation, and engineering design. Various empirical and semiempirical flow resistance models have been developed during the past century; however, a universal flow resistance model for varying types of rivers has remained difficult to be achieved to date. In this study, hydrometric data sets from six stations in the lower Yellow River during 1958–1959 are used to calibrate three empirical flow resistance models (Eqs. (5)–(7)) and evaluate their predictability. A group of statistical measures have been used to evaluate the goodness of fit of these models, including root mean square error (*RMSE*), coefficient of determination (*CD*), the Nash coefficient (*NA*), mean relative error (*MRE*), mean symmetry error (*MSE*), percentage of data with a relative error ≤ 50% and 25% (P_{50}, P_{25}), and percentage of data with overestimated error (*POE*). Three model selection criterions are also employed to assess the model predictability: Akaike information criterion (*AIC*), Bayesian information criterion (*BIC*), and a modified model selection criterion (*MSC*). The results show that mean flow depth (d) and water surface slope (S) can only explain a small proportion of variance in flow resistance. When channel width (w) and suspended sediment concentration (*SSC*) are involved, the new model (7) achieves a better performance than the previous ones. The *MRE* of model (7) is generally <20%, which is apparently better than that reported by previous studies. This model is validated using the data sets from the corresponding stations during 1965–1966, and the results show larger uncertainties than the calibrating model. This probably resulted from the temporal shift of dominant controls caused by channel change resulting from varying flow regime. With the advancements of earth observation techniques, information about channel width, mean flow depth, and suspended sediment concentration can be effectively extracted from multisource satellite images. We expect that the empirical methods developed in this study can be used as an effective surrogate in estimation of flow resistance in the large sand-bed rivers like the lower Yellow River.

1. Introduction

Flow velocity is a fundamental component of fluvial hydraulic geometry and sediment transport. The three classical flow velocity formulae include the Darcy-Weisbach equation

$$v = \left(\frac{8gRS_f}{f_r}\right)^{1/2}, \tag{1}$$

Chézy equation

$$v = C\left(RS_f\right)^{1/2} \tag{2}$$

and Manning equation

$$v = \frac{R^{2/3}S_f^{1/2}}{n} \tag{3}$$

where v is the mean flow velocity; R is the hydraulic radius; S_f is the friction slope (often approximated by water surface slope or channel slope, S); g is the acceleration caused by gravity, and f_r, C, and n are Darcy-Weisbach, Chézy, and Manning flow resistance coefficients, respectively (in SI units).

The central problem in applying these three equations is the estimation of flow resistance coefficients. Quantifying flow resistance can significantly contribute to flood routing, prediction of flow velocity, ecological habitat evaluation, engineering design, geomorphological regime theory development, and other scientific and practical applications (Bathurst, 2002; Ferguson, 2007).

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Investigations on flow resistance have survived for more than a century (Manning, 1891; Keulegan, 1938; Vanoni, 1941, 1946; Vanoni and Brooks, 1957; Qian et al., 1959; Peterson and Mohanty, 1960; Simons and Richardson, 1960; Vanoni and Nomicos, 1960; Simons et al., 1963; Qian and Zhou, 1965; Rouse, 1965; Golubtsov, 1969; Limerinos, 1970; Judd and Peterson, 1969; Bathurst, 1978, 1985, 2002; Bray, 1979; Hey, 1979; Davis and Sutherland, 1980; Griffiths, 1981; Jarret, 1984; Aguirre-Pe and Fuentes, 1990; Bennett, 1995; Dingman and Sharma, 1997; Nikora et al., 1998; Lee and Ferguson, 2002; Ferro, 2003; Ferguson, 2007, 2010; López et al., 2007; Recking et al., 2008; Reid and Hickin, 2008; Comiti et al., 2009; David et al., 2010; Robert, 2011; Ferreira et al., 2012; Nitsche et al., 2012; Schneider et al., 2015). Among these studies, the methods used for quantifying flow resistance can be generally categorized into two major groups: (i) a characteristic particle size approach (or a semiempirical approach) (Keulegan, 1938; Vanoni and Brooks, 1957; Qian et al., 1959; Simons and Richardson, 1960; Vanoni and Nomicos, 1960; Simons et al., 1963; Rouse, 1965; Judd and Peterson, 1969; Bathurst, 1978, 1985, 2002; Bray, 1979; Hey, 1979; Recking et al., 2008; Reid and Hickin, 2008), and (ii) a random field approach (or an empirical approach) (Jarret, 1984; Thorne and Zevenbergen, 1985; Rickenmann, 1994, 1996; Dingman and Sharma, 1997; Nikora et al., 1998; Comiti et al., 2007; Aberle and Smart, 2003; Aberle et al., 2010).

The semiempirical method has been advanced by the success of boundary layer and pipe flow theory proposed by Keulegan (1938), which relates flow resistance to relative submergence in the semilogarithmic form. This method has been successfully applied to predict flow resistance in low-gradient, gravel-bed channels and/or mountain streams, where flow resistance is dominated by grain roughness (Bathurst, 1978, 1985, 2002; Nikora et al., 1998; Lee and Ferguson, 2002; Ferguson, 2007). However, performance has been poor when this method is extrapolated to other streams in which the flow is controlled by different components of flow resistance, such as form roughness or spill roughness (Comiti et al., 2007; David et al., 2010). Thus, empirical approaches have been developed to represent the total flow resistance resulting from different sources of rough elements by which flow resistance (velocity or discharge) can be directly related to reliable, easily measurable channel properties or flow variables by statistical means (Golubtsov, 1969; Riggs, 1976; Jarret, 1984; Dingman and Sharma, 1997; Comiti et al., 2007; David et al., 2010). Among the variables included in the empirical analyses, mean flow depth and/or water surface slope (stream bed slope) are generally considered as the two most important. Some investigations have demonstrated that unit discharge or dimensionless unit discharge exerts an important influence on flow resistance (Rickenmann, 1991; Bjerklie et al., 2005a; Comiti et al., 2007; Ferguson, 2007; David et al., 2010; Rickenmann and Recking, 2011; D'Agostino and Michelini, 2015; Schneider et al., 2015). In fact, unit discharge or dimensionless unit discharge is physically equal to the product of mean flow depth and water surface slope in that it is the function of flow depth and water surface and usually preferable to the use of boundary shear stress for estimating incipient sediment motion in steep streams (Comiti et al., 2007). For streams where bedform roughness is dominant, a random field of bed elevations approach has been proposed (such as standard error of bed elevations and two-dimensional second-order structure function of bed elevations) to characterize flow-dependent sand bed roughness (Nikora et al., 1998; Aberle and Smart, 2003; Aberle et al., 2010).

Because of the complex controls on roughness, large uncertainties have been observed through extensive field observation (Bathurst, 2002; David et al., 2010). Flow resistance is dominant by various controls, which is difficult to completely explain. The existing relationships could not perform reliably over a wide range of flows and hydraulic conditions (Bathurst, 2002; David et al., 2010). Moreover, the uncertainty may result from the varying data sets obtained from different field investigations and flume experiments. The channel form and/or flow variables exhibit large spatial and temporal variability and substantial variability between the investigated sites or experiment design (David et al., 2010; Ferguson, 2010). A complete understanding of the controls on flow resistance has thus far eluded us.

Flow resistance in sand-bed rivers appears to be more complex than that in gravel-bed rivers, in that sand-bed rivers generally have more easily movable boundary conditions (Vanoni and Brooks, 1957; Simons and Richardson, 1960; Vanoni and Nomicos, 1960). Many efforts have also been devoted to developing flow resistance equations for sand-bed rivers (Vanoni, 1946; Qian et al., 1959; Simons and Richardson, 1960; Simons et al., 1963; Qian and Zhou, 1965; Rouse, 1965; Wang and White, 1993; Wright and Parker, 2004; Yang et al., 2005; Huybrechts et al., 2011; Cheng, 2016). Qian et al. (1959) and Qian and Zhou (1965) argued that roughness was closely related to a given grain size (D_{65}, 65% finer than). Yang et al. (2005) showed that total flow resistance in the large alluvial sand-bed rivers is dominated by sand dune height. The evidence from a large quantity of flume experiments and field investigations also demonstrated the importance of bedforms to flow resistance in sand-bed streams (Vanoni and Brooks, 1957; Simons and Richardson, 1960; Vanoni and Nomicos, 1960; Shen, 1962; van Rijn, 1984; Huybrechts et al., 2011). And various flow resistance models for bedform roughness, which worked independently under different flow conditions, have been proposed (Richardson et al., 1962; Lau, 1983; Wang and White, 1993; Julien and Raslan, 1998; Niemann et al., 2011). The effects of suspended sediment on channel bedform and flow resistance have also been investigated through a series of flume experiments (Vanoni and Nomicos, 1960; Arora et al., 1986; Lyn, 1991). The earlier results showed that the presence of suspended sediment could cause a reduction in flow resistance because of the damping effects of suspended sediment on flow turbulence (Vanoni, 1953; Vanoni and Nomicos, 1960). On the contrary, subsequent flume experiments indicated that the presence of suspended sediment could lead to an increase or a reduction in flow resistance (Arora et al., 1986; Lyn, 1991). Also, bedload transport will tend to increase flow resistance because of the work that the moving water does (Vanoni and Nomicos, 1960; Bjerklie, 2007). In rivers where the Froude number is <1, flow resistance will be affected by downstream conditions and by cross-channel turbulence and eddy viscosity; thus flow resistance is a three-dimensional characteristic of flow conditions. Therefore, flow resistance in sand-bed rivers is extremely complex because it is a function of flow regime (Richardson et al., 1962; Lau, 1983; Wang and White, 1993; Julien and Raslan, 1998; Niemann et al., 2011), sediment characteristics (Qian et al., 1959; Camenen et al., 2006; Cheng, 2016), and channel geometry (Simons and Richardson, 1960).

The lower Yellow River is a highly transport-limited sand-bed river with excessive suspended sediment concentration (Qian and Zhou, 1965; Wang et al., 2009b; Tables 1 and 2). The river channel bed is composed of fine sand (mean grain size <0.1 mm; Table 2). The high suspended sediment load in the lower Yellow River exerts great influence on channel morphology change (Qian and Zhou, 1965; Wang et al., 2009b; Ma et al., 2012). Although some investigations have studied flow resistance in the lower Yellow River (Qian et al., 1959; Qian and Zhou, 1965; Qin et al., 1995; Cheng et al., 1997; Sun et al., 2005), a clear recognition of the major controls on flow resistance is still lacking. Different from the previous flume experiments, this study aims to identify the major controls on flow resistance through a series of multivariate regression models, and we will discuss their roles in variation of flow resistance. We expect that the results will provide a better understanding of the controls on flow resistance in large sand-bed rivers and will contribute to flood routing in ungauged large sand-bed rivers like the lower Yellow River.

2. Study reaches

The lower Yellow River starts from Mengjin and flows into the sea at Lijin with a length of 768 km (Fig. 1A). The mean annual runoff of the Yellow River is about 37.89 billion m^3, and the mean annual suspended