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A study on limit velocity and its mechanism and implications for alluvial rivers

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ABSTRACT

Observations from field investigations showed that flow velocity greater than 3 m/s rarely occurs in nature, and high flow velocity stresses the bio-community and causes instability to the channel. For alluvial rivers without strong human disturbance, the flow velocity varies within a limited range, generally below 3 m/s, while the discharge and wet area may vary in a range of several orders. This phenomenon was studied by analyzing hydrological data, including daily average discharge, stage, cross sections, and sediment concentration, collected from 25 stations on 20 rivers in China, including the Yangtze, Yellow, Songhua, Yalu, Daling, and Liaohe Rivers. The cross-sectional average velocity was calculated from the discharge and wet area using the continuity equation. For alluvial rivers, the wet cross section may self-adjust in accordance with the varying flow discharge so that the flow velocity does not exceed a limit value. In general, the average velocity increases with the discharge increase at low discharge. As the discharge exceeds the discharge capacity of the banks, any further increase in discharge does not result in a great increase in velocity. The average velocity approaches an upper limit as the discharge increases. This limit velocity, in most cases, is less than 3 m/s. Human activities, especially levee construction, disturb the limit velocity law for alluvial rivers. In these cases, the average velocity may be approximately equal to or higher than the limit velocity. The limit velocity law has profound morphological and ecological implications on alluvial rivers and requires further study. Rivers should be trained and managed by mimicking natural processes and meeting the limit velocity law, so as to maintain ecologically-sound and morphological stability.

1. Introduction

An alluvial channel is usually located in the middle or lower reaches of a river, with its watercourse wandering and swaying slowly and finally forming a flat and wide valley (Chang, 1990). Where the river carries a heavy sediment load and the land is flat, the alluvial sediments may form a delta. An alluvial river is defined as a river with its boundary composed of sediment previously deposited in the valley, or a river with erodible boundaries flowing in self-formed channels (Wang et al., 2014). Over time the stream builds its channel with sediment it carries and continuously reshapes its cross sections to reach the depths of flow and channel slopes that generate the sediment-transport capacity needed to maintain the stream channel (Wang et al., 2014; Huelin-Rueda et al., 2014). The river morphology of alluvial rivers is relevant to many variables, including discharge, sediment transport rate, river width and depth, average flow velocity, hydraulic radius, channel slope and roughness.

Based on discussions regarding the characteristics of different river patterns, including mountain rivers, alluvial rivers, and estuaries, Chien et al. (1987) and Chien and Wan (1999) concluded that alluvial rivers have the ability of self-adjustment; that is, alluvial rivers can self-adjust in accordance with incoming water, sediment condition and boundary conditions. Riahi-Madvar et al. (2011) and Huang and Nanson (2002) suggested that a self-formed river flowing through its own alluvium tends to adjust its hydraulic geometry over time so that it can just transport the imposed sediment load without net deposition or scour. Representative formulas expressing the self-adjustment ability of alluvial rivers include Lacey's (1929) formula of equilibrium theory, Leopold and Maddock's (1953) geometry formula of the relations between velocity, water depth, river width, channel slope and discharge, Yang and Song (1979) minimum unit stream power theory, and Chang's (1979) minimum stream power theory. Xie (1997)

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summarized five characteristics of the self-adjustment ability of alluvial rivers.

This paper proposes the limit velocity law, which is a noticeable phenomenon in natural streams. Field investigations found that the flow velocity in natural alluvial rivers is generally not more than 3 m/s. Zhang et al. (2007) pointed out that due to the mild slope and wide floodplain of an alluvial river, the flow velocity is not more than 2–3 m/s. Aquatic life forms adapt well to the water environment in which the flow velocity is not more than 3 m/s. Wang et al. (2007) analyzed the survival environments of 36 kinds of fish around the world, and found that 90% of adult fish cannot survive when the flow velocity is more than 2 m/s; for example, Chinese sturgeon cannot survive when the flow velocity is more than 1.5 m/s.

To verify the field observation that the flow velocity in natural alluvial rivers is generally less than 3 m/s and to summarize the flow velocity law for alluvial rivers, this paper analyzed observed hydrological data, and used the continuity equation to calculate flow velocity. The limit velocity law for alluvial rivers was derived based on results from the analyses. Furthermore, this paper analyzed why the limit velocity law exist in alluvial rivers, showed the ecological and morphological implications of this law, and proposed the resistance principles of river training and management.

2. Methods

This study chose 25 stations on 20 rivers in China, including the Yangtze, Yellow, Songhua, Yalu, Daling, and Liaohe Rivers. For each river, data were collected at one, two or three hydrological stations. Hydrological data included the daily average discharge, daily average stage, cross sections, and sediment concentration. The data were recorded from 1950 through 1988, except the data for the Liuhe and Xiliao Rivers, for which the period of the data was from 1935 through 1988. The monthly range of the data was determined by each river's physical state. The study was effective only when the data were collected during the non-freezing period. Therefore, the data of the Yangtze River were from January through December, the data of the Yellow River were from May through December, and the data of the Songhua, Yalu, Daling, and Liaohe Rivers were from May through October, respectively.

The boundary of a cross section comprises the channel boundary and the water-surface profile. The wet area is the area enclosed by the boundary. Hydrological yearbooks provide data at the gauged sections. The cross-sectional average velocity was calculated from the discharge and wet area using the continuity equation. Velocity∼discharge curves from representative alluvial rivers and mountain rivers were plotted to obtain the limit velocity law. The mechanisms of the limit velocity were analyzed from two aspects: one was based on the self-adjustment of the sediment transport capacity of alluvial rivers; and the other was based on the relation between the limit velocity and critical velocity of the suspended load. During the process of this analysis, the curves of cross sections, velocity and discharge, discharge and area, and critical velocity of suspended load motion and particle size were used.

3. Results

3.1. Concept of limit velocity

In general, the average velocity increases with an increase in the discharge when the discharge is low. As the discharge exceeds the discharge capacity of the banks, any further increase in discharge does not result in a great increase in velocity. The average velocity approaches an upper limit, i.e. the limit velocity. The limit velocity, in most cases, is below 3 m/s.

Fig. 1 shows the *V*–*Q* (which is the abbreviation for velocity–discharge) relation curves for alluvial rivers based on data from the Caijiagou station on the Lalin River, the Wudaogou station on the Huifa River, the Jilin station on the Songhua River, and the Ayanqian station on the Nenjian River. The Lalin and Huifa Rivers are tributaries of the Songhua River. With an increase in the discharge, the average velocity approaches the limit velocity. As shown in Fig. 1, the limit velocity is 1.30 m/s at the Caijiagou station, 1.73 m/s at the Wudaogou station, 2.00 m/s at the Jilin station, and 1.86 m/s at the Ayanqian station. The limit velocity for the above alluvial rivers does not exceed 3 m/s.

3.2. Mechanisms of the limit velocity

This study analyzed mechanisms of the limit velocity from two aspects, including the mechanism based on the self-adjustment of the sediment transport capacity of the alluvial rivers and the mechanism

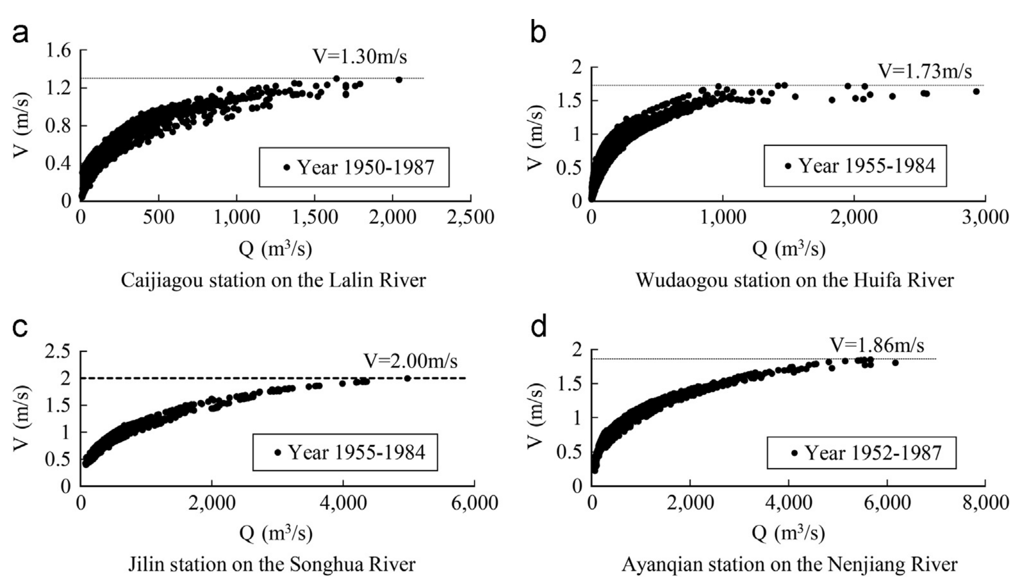

Fig. 1. *V*–*Q* relations of typical alluvial rivers.