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Reconstruction of stage–discharge relationships and analysis of hydraulic geometry variations: The case study of the Pearl River Delta, China

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ABSTRACT

Long-term variations of the stage–discharge relationships can reflect the channel morphology changes that can be caused by both natural factors and human activities. The rating curves are usually employed to predict discharges at monitoring hydrometric sections of interest. In this paper, the variation of rating curves is investigated with the purpose of understanding the extent of the impacts of human activities on the dramatic changes in channel morphology. To this end, the Pearl River Delta (PRD), which has suffered intensive human interferences in the recent decades, is selected as case study. Firstly, the stage–discharge relationship variation is analyzed on the basis of daily data recorded at Makou and Sanshui stations located at the apex of the delta during the flood season from 1955 to 2005. Secondly, the Mann–Kendall test and Pettitt test are used to detect trends and abrupt change points in the rating parameters. The result shows that the rating calibration parameters ln$a$ and b have an increasing and a decreasing trend respectively with an abrupt change point around 1980 for the gauging stations. The rating curves established at different periods demonstrate evident downward shifts, indicating that water stages become lower in terms of the same amount of discharge. This temporal variation of the rating curves is unlikely to be caused by natural changes during the study period in the PRD region, because, in general, channel morphology varies slowly under natural effects. However, in reality, the channel morphology at PRD region has changed tremendously due to large-scale and long-term sand excavation in this region. Then, the rating curve from 1955 to 1980 is here applied to estimate potential water stage (from 1981 to 2005) by assuming low human impacts. The results show that the percentage deficits of the mean annual effective water stages show an increasing trend with time at both stations, and attained the maximum value in the last time period, 40.6% at Makou and 79.2% at Sanshui, respectively. This indicates that the amplitude of the impact of sand excavation on the relationship between water stages and discharges at Sanshui Station is larger than that at Makou Station. Finally, a ternary diagram is plotted to test the variation of hydraulic geometry exponents (p, f, and m) at different time periods. Here p, f and m are the exponents of the power laws between section width, water depth and flow velocity and discharge. The variations of the ratio of width to the maximum depth of the main channels over the PRD can also prove that the riverbed downcutting is significant. These indicate that the hydraulic geometry of the PRD had no obvious change trends before the 1980s, but displayed a significant change trend hereafter, due to the accumulation of channel changes by extensive sand excavation in the PRD.

1. Introduction

The relationships between water stages and discharges play an important role in flood control (Parodi and Ferraris, 2004; Bormann et al., 2011), water resource planning (Sahoo and Ray, 2006) and management (DeGagne et al., 1996). In order to understand this important relation, the rating curve can be established by plotting the measured discharges against the corresponding stages and drawing a smooth curve of the relation between the two quantities (Herschy, 1995). The rating curve is particularly important for rivers that carry large volumes of water and the curve may change when channel of dams, levee and bridges, diversion of bed material and/or flow and change of land use (morphology changes (Rantz, 1982a; Schmidt and Yen, 2001; Schmidt, 2002; Braca and Futura, 2008). However, in addition to climate-induced changes and variations, human activities such as sand excavation and construction Ye et al., 2003) can also make the rating curve shift trending up and down. The phenomenon reflects the complexity of the interaction between the river flow and channel morphology (Lu et al., 2007; Luo et al., 2007).

The rating curve has been and is currently used extensively as a tool in hydrology to describe the relationship between water stage and discharge in natural and/or artificial open channels. The current practice of

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defining and applying stage–discharge ratings can be traced back to the early 20th century and a great portion of the modern practices used worldwide were developed by the U.S. Geological Survey (Corbett et al., 1943; Dawdy, 1961; Rantz, 1982a,b).

There are many approaches and techniques for studying stage–discharge ratings. Schmidt and Yen (2001) examine the relationship of stage and discharge in open channels based on the fundamental hydrodynamics of unsteady non-uniform flow, and identified terms in the Saint–Venant equations that should be considered in rating development. Bhattacharya and Solomatine (2000) use Artificial Neural Networks (ANNs), in fact, a broad term covering a large variety of network architectures, the most common of which is a multilayer perceptron (MLP), for defining stage discharge relations. Such a network is trained by the so-called error back propagation method, which is a specialized version of the gradient-based optimization algorithm. A comparison to a conventional statistical stage–discharge model has shown the superiority of an approach using ANNs. Several publications deal with the uncertainty in defining rating curves or the influence of uncertainty in peak discharge evaluation (Clarke, 1999; Parodi and Ferraris, 2004). Sivapragasam and Muttil (2005) suggest the use of Support Vector Machine in the extrapolation of rating curves, which work on the principle of linear regression on a higher dimensional feature space. However, the most commonly used rating curve treats the discharge as a unique function of the stage. The rating typically is a power curve of the form given by the following (Rantz, 1982b; Herschy, 1995; Schmidt, 2002; Leon et al., 2006; Braca and Futura, 2008):

$$Q = a(h-h_0)^b \tag{1}$$

or a linearized equation based on natural logarithm transformation:

$$\ln Q = \ln a + b\ln(h-h_0) \tag{2}$$

where Q is the discharge (m^3/s), h is the water stage or gauge height (m), and a, h_0 and b are the rating calibration parameters. a is the discharge when $(h - h_0)$ is equal to 1; h_0 is not the gauge height of some identifiable feature on the irregular section control or in the channel, but actually a mathematical constant that is considered as a gauge height to preserve the concept of a logarithmically linear stage–discharge relation; b is the slope of the rating curve (on logarithmic paper); $(h - h_0)$ is the effective depth of water on the control (the effective water stage). Generally, before deriving the parameters a and b by regression analysis, h_0 is determined by using a methodology comprised of the minimization of root mean square error (RMSE) between the measured discharge and the calculated discharge (Leon et al., 2006). Especially, parameters a and b are specific to a channel cross-section. They can be related to the physical characteristics of the river. a is a scaling factor that includes the section width, Manning coefficient and the local bottom slope. b includes the geometry of the river banks, in particular the departure from vertical banks and generally an indicator of the type of control acting on the stage–discharge relation (Rantz, 1982a). As the rating curve is relatively easy to develop and presents a clear view of the stage–discharge relations, it has been widely used for engineering and scientific purposes, such as estimating discharge, predicting flood, and adjusting the position of freshwater intake (Leon et al., 2006; Lu et al., 2007; Jalbert et al., 2011).

The Pearl River Delta (PRD) is one of the fastest developing regions in China. This complicated delta distributaries have a density of 0.68–1.07 km/km^2. Due to the region's booming economy and intensive human activities, new environmental problems emerge in recent decades, which include floods, water contamination and storm surge (Ho and Hui, 2001; Luo et al., 2002; Mai et al., 2002; Liu et al., 2003; Lu et al., 2007; Guan et al., 2009). In fact, from 1993 to 1998, the PRD region suffered repeatedly from flooding disasters. Two huge floods, 50-year return period and 100-year return period respectively, occurred in June 1994 and June 2005 (designated as "94.6" and "05.6" respectively). The 1994 Pearl River flood, in particular, caused great demand and it was estimated that the direct losses exceeded $2 billion (Liu et al., 2003). What is surprising, however, is that the water stages of "94.6" and "05.6" were lower by 1.28 m and 2.45 m at a discharge rate of 3000 m^3/s than the flood in 1989, which was a relatively small flood at the time (Luo et al., 2007). Previous studies have analyzed the variations in the water stage and discharge in the PRD region, respectively (e.g. Zeng et al., 1992; Huang et al., 2000; Yang et al., 2002; Liu et al., 2003; Chen et al., 2004; Zhang et al., 2009b). Some work indicated that the discharge from the upper river displays no obvious changes, but the changing trends of the water stage showed different features in different parts of the PRD region. Generally speaking, in the upper part of the delta, the water stages showed a decreasing trend while in the middle and lower parts there was an increasing trend (Zhang et al., 2009b). The relations between water stage and discharge, however, have never been studied in this region. Furthermore, the relations between water stage and discharge can quantitatively reflect the morphological changes in channels (Rantz, 1982a; Schmidt, 2002; Braca and Futura, 2008; David et al., 2010). Therefore, the objectives of this paper are: (1) to detect the variations of the rating parameters derived from the long-term daily records of water stages and stream discharges at gauging stations during the flood seasons; (2) to reconstruct rating curves and quantify the impact of sand excavation on the lowering water stage by comparing the difference between the estimated and measured values from different periods; and (3) to analyze the associated hydraulic geometry variations to better explain the underlying causes of the changes in stage–discharge relations in the PRD region.

2. Study area and datasets

The Pearl River, 13th largest river in the world, is the second largest river in China in terms of mean annual water discharge (336 billion m^3, Pearl River Water Resources Committee (PRWRC), 1991) (Fig. 1) The drainage basin is situated between 21.31°–26.49°N and 102.14°–115.53°E. Straddling the Tropic of Cancer, it covers a region of subtropical to tropical monsoon climate. From April to September (the flood season), about 95% of the sediment load and 80% of the water discharge are delivered, while only 5% and 20% of these are delivered during the dry season, which lasts from October to March (Xia et al., 2004). It is a compound water system including three principal rivers: the East River, the North River and the West River. These three rivers empty into the Pearl River estuary to form the Pearl River Delta (PRD). The streamflow yield is nonuniformly distributed in the Pearl River Basin (Zhang et al., 2007). The contributions of the West River, North River and East River to the PRD in terms of discharge are 77%, 15% and 8% respectively. The West River and the North River are the most important rivers in the Pearl River system. Geographically, waters from the West River and North River enter the delta network through Makou Station and Sanshui Station (Fig. 1).

Makou Station and Sanshui Station are the most important stations in the PRD because they are located at the apex of the delta and they record the amount of discharge entering the West River networks and the East River Networks. In this paper, daily (1955–2005) water stage and discharge data recorded at these two gauging stations are obtained from the hydrological yearbooks of China, whose reliability and homogeneity are strictly inspected by the authorities before they were published. Although Makou and Sanshui Station are closed to the tidal limits and mainly controlled by the streamflow from the upper river, they are still obviously influenced by the tide in dry seasons. Therefore, the daily data in dry seasons (from October to March) were not considered in this study to avoid the occurrence of the looped curve of the stage–discharge relations.