Changes in stage–flow relation of the East River, the Pearl River basin: causes and implications

Qiang Zhang, Kun Li, Vijay P. Singh, Xiaohong Chen and Jianfeng Li

ABSTRACT

Water level and streamflow extracted from 891 hydrological episodes from both dry and flood seasons covering a period of 1954–2009 were analyzed to investigate stage–flow relations. Results indicate the following. (1) Since the early 1990s the low/high flow is increasing/decreasing. The water level, particularly the high level, is consistently decreasing. An abrupt decrease of water level is observed since the early 1990s at the lower East River. (2) Stage–streamflow relation is usually stable in the river reach with no significant bedform morphological changes. Changes in the geometric shape of the river channel are the major cause of the change in the stage–streamflow relation. (3) An abrupt decrease of water level at the Boluo station is mainly the result of abnormally rapid downcutting of the riverbed due to extensive sand dredging within the channel which caused serious headwater erosion. This human-induced modification by downcutting of the river channel may lead to significant hydrological alterations and may have critical implications for flood control, conservation of eco-environment, and also for basin-wide water resources management in the lower East River basin.

Key words | bedform morphology, fluvial processes, hydrological alteration, stage–streamflow relation, East River

Qiang Zhang (corresponding author)
Kun Li
Xiaohong Chen
Jianfeng Li
Department of Water Resources and Environment,
Sun Yat-sen University,
Guangzhou 510275,
China;
Key Laboratory of Water Cycle and
Water Security in Southern China of Guangdong
High Education Institute,
Sun Yat-sen University,
Guangzhou 510275,
China;
School of Geography and Planning,
and Guangdong Key Laboratory for Urbanization
and Geo-simulation,
Sun Yat-sen University,
Guangzhou,
China
E-mail: *zhangq68@mail.sysu.edu.cn*

Vijay P. Singh
Department of Biological & Agricultural
Engineering and Department of Civil and
Environmental Engineering,
Texas A & M University,
College Station, Texas 77843-2117,
USA

INTRODUCTION

Human activities, including construction of dams, diversion structures, levees, among others, in addition to climate changes, alter river behavior (e.g., Dudgeon 1995; Harmar *et al.* 2005). Revenga *et al.* (2000, cited in Tharme 2003) have estimated that 60% of the world's rivers are fragmented by hydrologic alterations, with 46% of the 106 primary watersheds modified by the presence of at least one large dam. China alone possesses nearly half of the total number of dams in the world (Tharme 2003). However, without construction of water reservoirs, other human activities, such as sediment mining, bank revetment, and artificial cutoff, can also be thought of as major human disturbances (e.g., Li *et al.* 2007). River channel changes as a result of human activities usually trigger many consequences, such as flood control (Shi *et al.* 2007), navigation management, malfunctioning of the hydraulic facilities, instability of river banks, and also alteration of aquatic and riparian ecosystems (Hanrahan 2007). Therefore, river channel changes and related altered hydrological regimes have been receiving increasing attention from fluvial geomorphologists, hydrologists, and also water resources management practitioners (e.g., Surian 1999; Surian & Rinaldi 2003). Although erosion, sand mining, deforestation, urbanization, channelization, flow regulation, water transfer, irrigation, salinization, and domestic and industrial pollution, have altered rivers, the influence of these and other human activities is not fully understand (Dudgeon 1995). This constituted the motivation for this study.

The East River is one of the tributaries of the Pearl River, the third largest river in China in terms of streamflow. The length of the East River is 562 km with a drainage area

doi: 10.2166/nh.2012.194

of 35,340 km^2. The East River basin is high in the northeast parts and low in the southwest parts. The lowlands and hilly mountains are about 50–500 m high, accounting for 78.1% of the river basin and plains with an altitude of <50 m account for about 14.4% of the river basin. The mountains with an altitude of >500 m account for 7.5% of the river basin area. The long-term average annual precipitation is about 1,500–2,400 mm with more than 80% of the annual total precipitation during April–September. Based on the hydrological records at the Boluo station (Figure 1), the long-term annual average sediment discharge is 0.11 kg/m^3 and the long-term annual average sediment load is 2.66 million tons. Water resources in the East River are of great importance for the sustainable development of the regional socio-economy (Zhang *et al.* 2009d).

Due to increasing requirements of water resources as a result of the rapid growth of the population and booming socio-economy in the Pearl River Delta (PRD) region, water resources in the East River basin have been highly developed and heavily committed for a variety of uses, such as water supply, hydropower, navigation, irrigation, and suppression of seawater invasion (Chen *et al.* 2011). In recent years, the East River has provided the water supply of about 80% of Hong Kong's annual water demands (Chen 2001; Wong *et al.* 2010). In this sense, the availability and vulnerability of the East River water resources systems will be of great importance for sustainable social and economic development in the PRD, and also for sustainable water supply for large cities, such as Hong Kong, Macau, and so forth. However, the hydrological regimes of the East River are heavily affected by the river channel changes due to downcutting processes of the riverbed.

Booming construction industry is leading to a tremendous demand for building materials. One of the biggest consequences of this boom is the serious downcutting of riverbeds, which highly influences the hydrological process. The downcutting of riverbeds is reported in many regions. In the upper Mississippi River basin, 4.26×10^7 metric tons of gravel and sand were excavated in 1950, and this number doubled to 8.35×10^7 metric tons around 1960 (Lagasse & Winkley 1980). In Italy, the Tagliamento River has been subjected to sediment mining in recent decades, and more than 24 million cubic meters of sediments were extracted from 1970 to 1991 (Rinaldi *et al.* 2005). In the Pearl River, downcutting of river channels is also a serious issue. Investigations (Chen & Chen 2002) indicate that rapid and intensive downcutting processes of river channels in the upper PRD occurred after the mid-1980s, including lower reaches of the East River. Since 1985, the sand sediments dredged annually are about 0.05–0.06 billion cubic meters, which is the direct cause for the intensive downcut of riverbed of the upper PRD (Chen & Chen 2002). However, the amount of sediments dredged during 1990–1993 accounted for more than half of the total sediment mined during recent decades, which heavily influenced morphological properties of the river channels of the upper PRD. A study by Luo *et al.* (2007) indicated that from 1986 to 2003, about 0.87 billion cubic meters of sand were excavated, which caused an average downcutting depth of 0.59–1.73, 0.34–4.43 and 1.77–6.48 m in the main channel

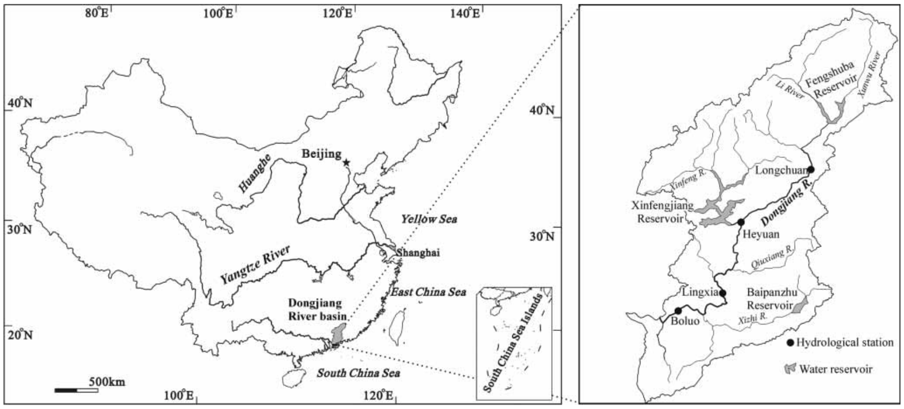

Figure 1 | Location of the study region and hydrological stations considered.

of the West River, North River, and East River, the major water systems in the PRD, respectively. Before the mid-1980s however, the scouring and filling of the river channels were in dynamic balance or in slight deposition. The sediment load dredged during 1980–1998 accounted for the net sediment that had accumulated within 70–125 years (Huang & Zhang 2006). The river channel in the upper PRD was greatly altered due to in-channel dredging and levee construction after about the mid-1980s, resulting in decreasing water level (Lu *et al*. 2007).

The above investigations focused on river channel changes in the upper PRD, and the West River in particular (e.g., Lu *et al*. 2007; Luo *et al*. 2007; Zhang *et al*. 2011). However, no reports are available concerning river channel changes and related impacts on hydrological regimes in the East River basin. Due to the critical role of the East River in water supply and the intensifying influence of regulated hydrological regimes on fluvial ecological environment, river channel changes and possible impacts on hydrological regimes need to be investigated. The objectives of this study therefore were: (1) to investigate changes in high flows; (2) to analyze changes in river cross sections; and (3) to evaluate the impact of river channel changes on flow regime and related implications.

DATA AND METHODOLOGY

We collected 260 water level and streamflow data sets covering the period 1979–2009 at the Heyuan station, 366 sets covering 1956–2009 at the Lingxia station, and 265 sets covering 1954–2009 at the Boluo station. In addition, data on river cross sections, mainly river depth, and geometric properties of the river channel at the Longchuan, Heyuan, Lingxia, and Boluo stations during 1965–2009 were collected. Locations of the hydrological stations in the study region are shown in Figure 1. Data were obtained from the Data Center of the Hydrological Bureau of the Guangdong province which firmly controls the quality of data following Chinese national standards. Correlation analysis was performed for the relation between water level and streamflow. As well, linear regression was used to analyze general trends within hydrological components considered in the study. To investigate the influence of fluvial geometric shapes on extreme flows, i.e., high flow or low flow processes, we analyzed changes in high flow and low flow and water levels and built linkages between high flow and low flow changes and riverbed alterations.

RESULTS

Changes in high and low flows and relation between water level and streamflow

Temporal changes in high flow, low flow, and mean flow and the difference between high and low flows at the Heyuan station are shown in Figure 2(a). It can be seen that no changing patterns were evident. In general, these flows were decreasing from 1979 to the late 1990s and were increasing after the 1990s. Specifically, mean flow and low flow have slightly increasing trends which can be detected by linear regression. High water level and low water level corresponding to high flow and low flow, respectively, and also mean water level were decreasing consistently during the entire time interval considered (Figure 2(b)). In particular, high water level seemed to exhibit a higher decreasing magnitude than low and mean water levels. As well, the coefficient of variation of streamflow changes indicates decreasing streamflow fluctuations with time (Figure 2(c)).

The relation between water level and flow at the Heyuan station is shown in Figure 3. This relation is good during high flow periods as shown in the right panel of Figure 3, but is not good during low flow periods as shown in the left panel of Figure 3.

Figure 4(a) shows that low flow at the Lingxia station is increasing, whereas high flow, mean flow and the difference between high and low flow are decreasing. The low water level is slightly increasing, whereas mean and high water levels are decreasing (Figure 4(b)). Also, streamflow fluctuations are decreasing during the time period considered in the study. The relation between flow and water level is stronger at the Lingxia station (Figure 5) as compared with that at the Heyuan station (Figure 3). Based on scatter points, the correlation between low flow and water level is lower than that between high flow and water level.

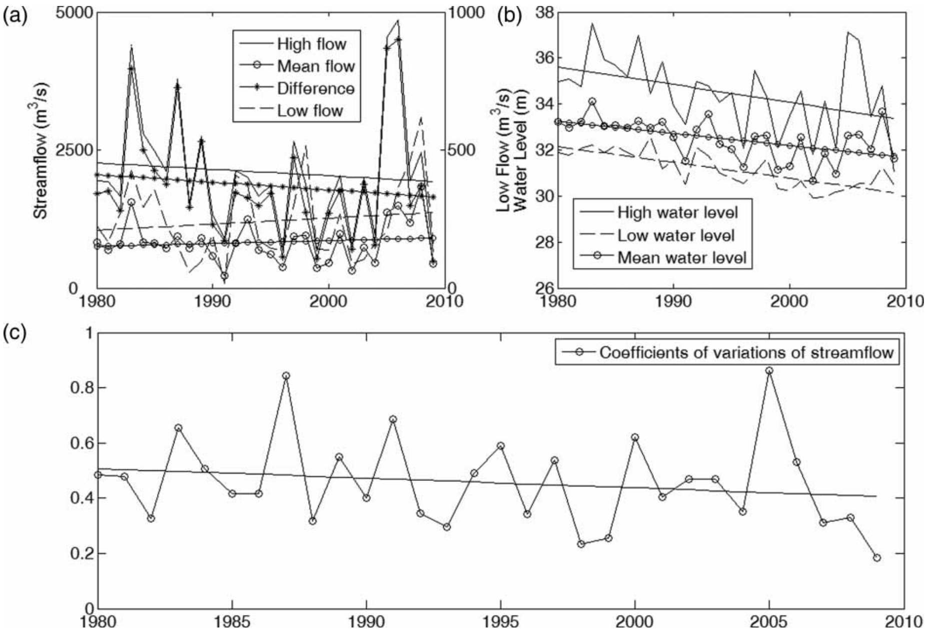

Figure 2 | The changes in streamflow and water level at the Heyuan station. (a) Changes in the high flow, mean flow, low flow and the difference between high and low flows. The right vertical axis is used for the low flow, and the left vertical axis is used for the other three kinds of streamflow. (b) Changes in high water level, mean water level, and low water level. (c) The change in coefficients of variations of streamflow. The straight lines denote the linear trends of the corresponding data.

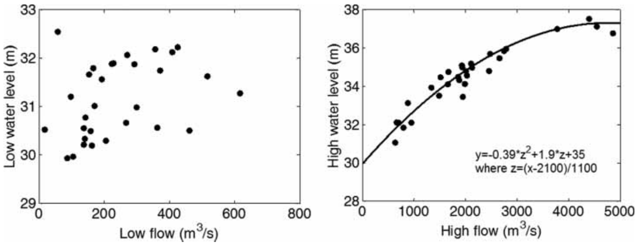

Figure 3 | Relations between the low water level and low streamflow (left panel), and also between the high water level and high streamflow (right panel) at the Heyuan station.

Similarly, low flow at the Boluo station is increasing, and other flow components are decreasing (Figure 6(a)). However, the changing behavior of water level at the Boluo station is distinctly different from that at the Lingxia and Heyuan stations (Figure 6(b)). A slight increase can be found for high and mean water levels. Nevertheless, an abrupt decrease in water levels such as high water level, low water level, and mean water level can be observed after the early 1990s. Streamflow variability represented by the coefficient of variation is decreasing (Figure 6(c)). The relation between flow and water level is poor, as represented by scatter points (Figure 7). Specifically, there seems to be no relation between low flow and water level, and the relation between high flow and water level points to large uncertainty. The relation between flow and water level before and after the early 1990s is illustrated in Figures 8 and 9. It can be seen from Figure 8 that the relation between high (low) streamflow and corresponding water level is suggestive. However, after the early 1990s, the flow versus water level relation is contaminated, as represented by scatter points. Stage versus flow relations should be consistent, if no topographical alterations of the river channel occur. In this case, we collected and analyzed bedform morphology data with the aim of investigating possible causes behind the altered stage versus streamflow relation, and this will be discussed in the next section.

Changes in geometric properties

Morphological changes in the riverbed at the Longchuan station are illustrated in Figure 10. As shown in Figure 1, the Longchuan station is upstream of the other three hydrological stations. It can be seen from Figure 10 that parts of the riverbed at the Longchuan station are undergoing downcutting. However, the magnitude of downcutting is not

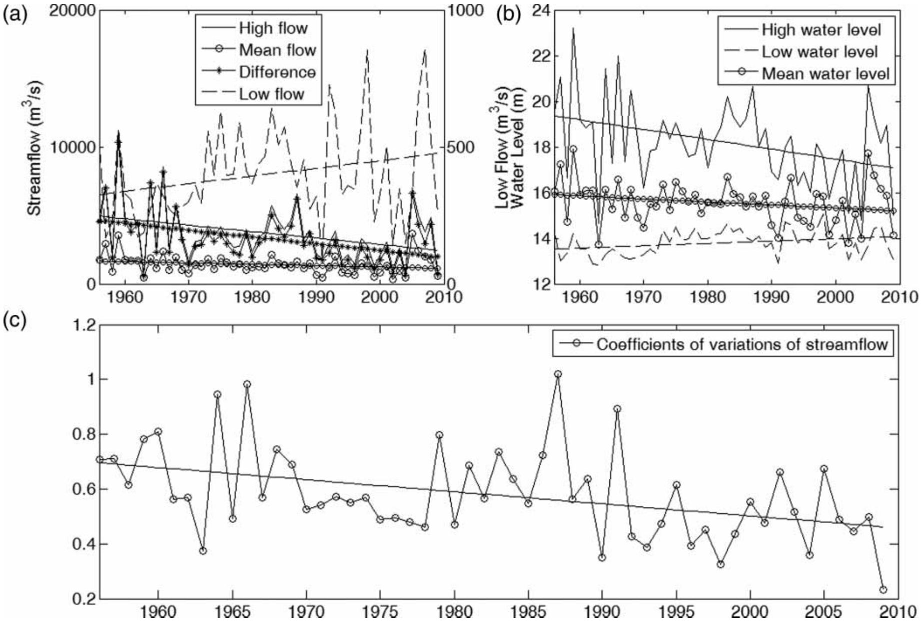

Figure 4 | The changes in streamflow and water level at the Lingxia station. (a) Changes in high flow, mean flow, low flow and the difference between high and low flows. The right vertical axis is used for the low flow, and the left vertical axis is used for the other three kinds of streamflow. (b) Changes in high water level, mean water level, and low water level. (c) The change in coefficients of variations of streamflow. The straight lines denote the linear trends of the corresponding data.

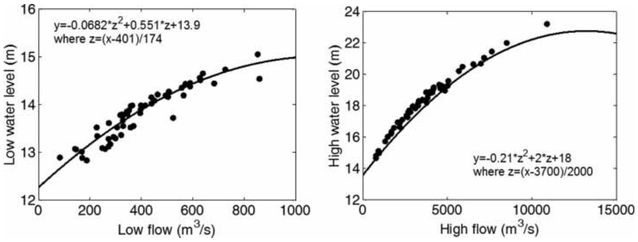

Figure 5 | Relations between the water level and streamflow at the Lingxia station.

evident. Also, changes in the riverbed during high flow periods, such as June (right panel Figure 10), are somewhat obvious when compared to those during low flow periods (left panel Figure 10). Riverbed changes are evident at the Heyuan station and it is particularly the case in the flood season, such as June. The largest depth of downcutting is about 3 m, from 1998 to 2007. The magnitude of riverbed change in low flow seasons is smaller than in high flow seasons (Figure 11). Changes in the trough point of the riverbed are shown in the inset in Figure 11. After about 1987 the trough of the riverbed was subjected to evident downcutting.

At the Lingxia station, however, the bedform morphology was subjected to slight variations (Figure 12). The geometric shapes of the river channel were relatively consistent and no evident changes were observed. However, significant modifications in the bedform morphology were found for the cross section at the Boluo station (Figure 13). Moreover, changes in the riverbed morphology were obvious in low flow periods, e.g., March and April. The riverbed morphology changes in high flow periods but are not shown here due to the lack of data. Generally, larger changes in the riverbed should occur in high flow periods due to significant scouring by the stronger hydrodynamic energy of flood waters. However, in this case, the riverbed morphology was subjected to considerably large downcutting in the low flow season. The inset plot of Figure 13 shows that abrupt deepening of the riverbed occurred after about the early 1990s. Possible causes behind the changes in the riverbed morphology and the likely linkage between altered stage versus flow relation and riverbed morphology will be discussed in the following section.

DISCUSSION

The variations of hydrological process are the complex results of anthropologic activities and climate change.

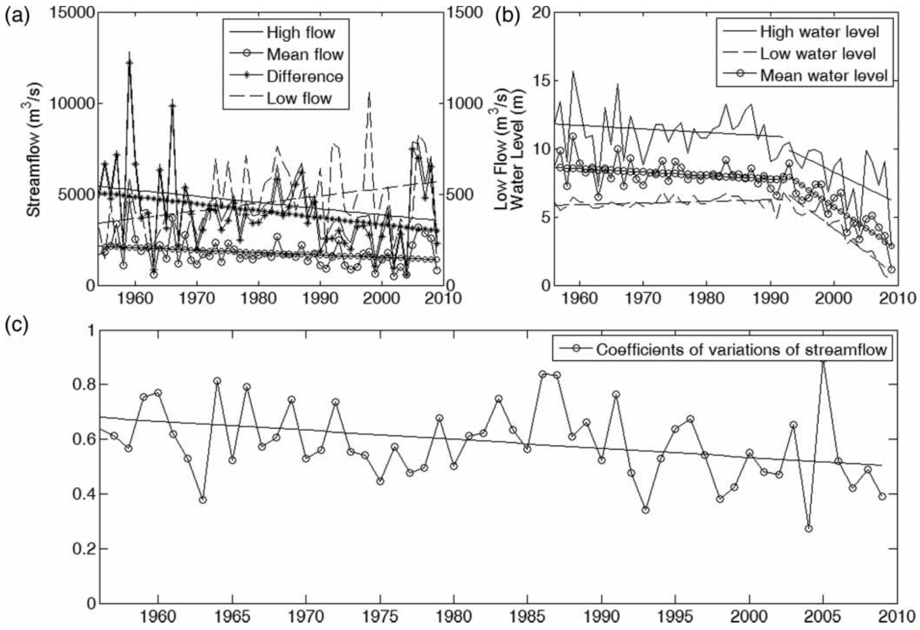

Figure 6 | The changes in streamflow and water level at the Boluo station. (a) Changes of the high flow, mean flow, low flow and the difference between high and low flows. The right vertical axis is used for the low flow, and the left vertical axis is used for the other three kinds of streamflow. (b) Changes in high water level, mean water level, and low water level. (c) The change in coefficients of variations of streamflow. The straight lines denote the linear trends of the corresponding data.

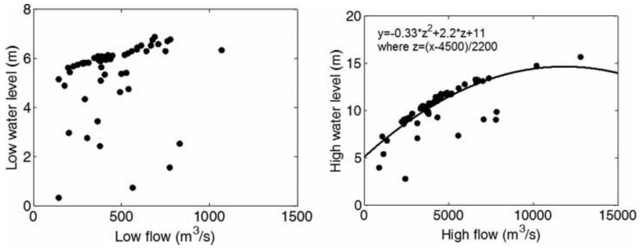

Figure 7 | Relations between the water level and streamflow at the Boluo station.

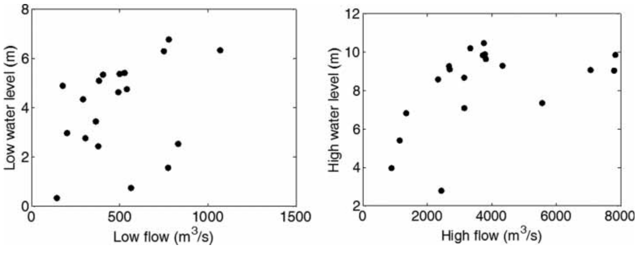

Figure 9 | Relations between water level and streamflow during 1990–2009 at the Boluo station.

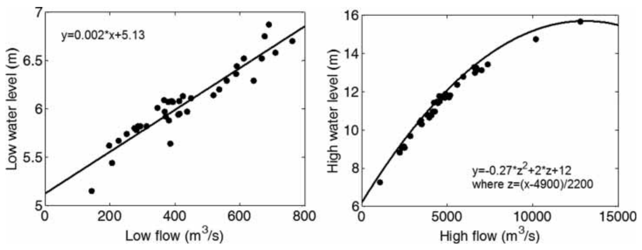

Figure 8 | Relations between water level and streamflow during 1954–1990 at the Boluo station.

However, the annual total precipitation in the East River shows no significant trends, although the number of rainy days is significantly decreasing (Zhang *et al.* 2009a). Zhang *et al.* (2010c) used the National Centers for Environmental Prediction of the National Center for Atmospheric Research (NCAR/NCEP) reanalysis data set to analyze the abrupt behaviors, trends, and periodicity properties of water vapor flux and moisture budget of east, south, west, and north edges of the Pearl River basin. The results indicated that in the east edge, the water vapor flux in spring and summer slightly decreased, and no obvious changes in autumn and winter were detected after the early 1960s. These relatively stable changes in precipitation and water vapor flux are relatively small and compared with human activities, the influences of precipitation changes on the stage–streamflow relation are very limited.

Changes in riverbed topography have the potential to alter the hydraulic characteristics of the river (Shi *et al.*

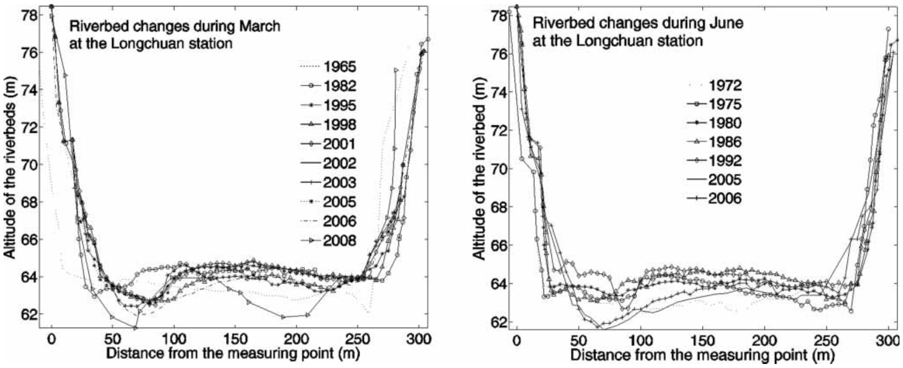

Figure 10 | Riverbed changes in altitude during March and June at the Longchuan station.

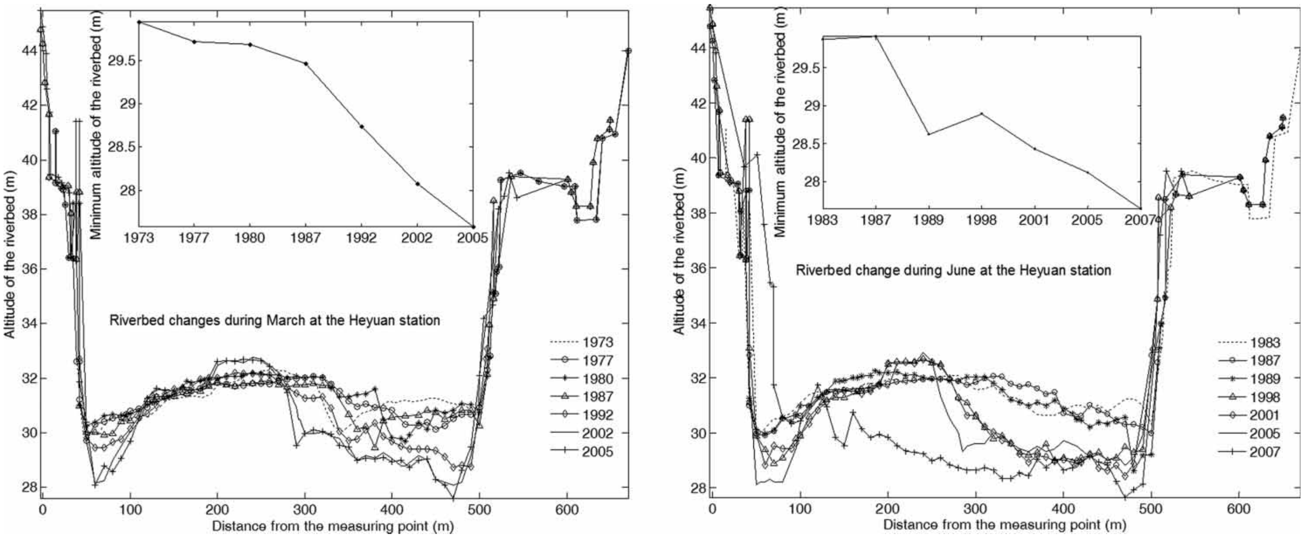

Figure 11 | Riverbed changes in altitude during March and June at the Heyuan station. The inset plots are the changes in the minimum altitudes of the riverbed.

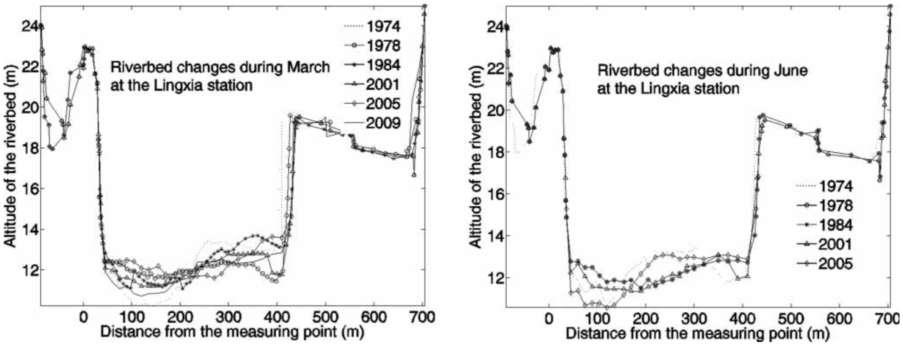

Figure 12 | Riverbed changes in altitude during March and June at the Lingxia station.

2007), including the relation between flow and water level. Changes in geometric shapes of the river channel may have considerable implications for flood control. The results of this study illustrate that the water level in the river reach characterized by changes in bedform morphology is usually subject to large fluctuations. Stage–flow relations are also contaminated by changes in the bedform morphology, such as at the Heyuan and Boluo stations. No obvious

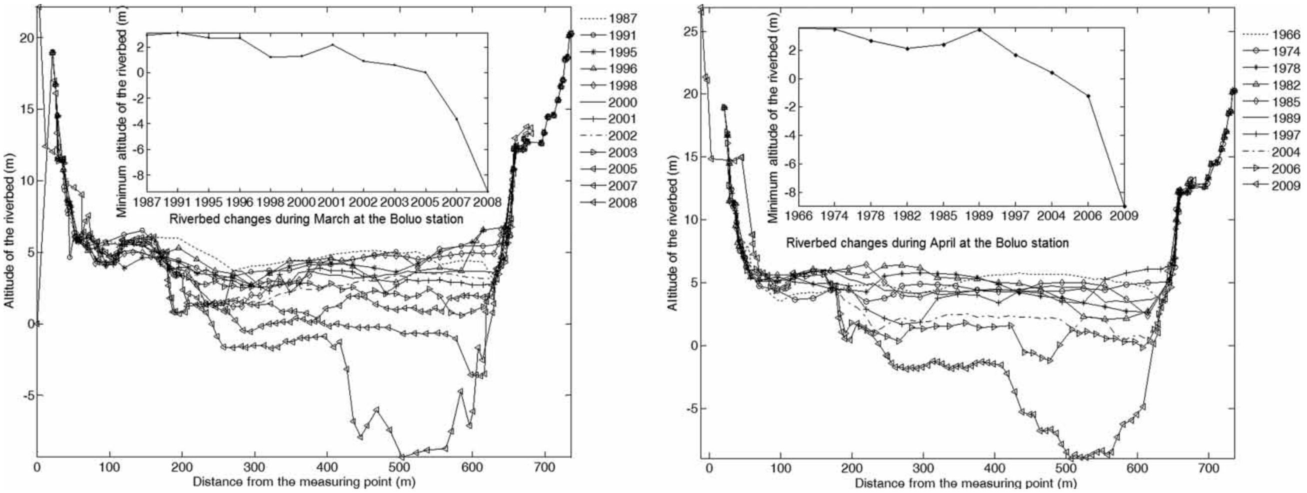

Figure 13 | Riverbed changes in altitude during March and April (the upper and the middle panels) at the Boluo station. The inset plots are the changes in the minimum altitudes of the riverbed.

changes are observed in the bedform morphology at the Lingxia station, and thus the relation between water level and flow is considerably steady. Alterations in bedform morphology can be taken as a major cause of the altered stage–flow relation and the water level change.

The Boluo station is located at the lower East River, and the river channel at this station is significantly influenced by the headwater erosion as a result of downcutting within the river network over the PRD (Zhang *et al.* 2010a). Generally, sand mining or dredging with the aim to satisfy the requirements arising from rapid economic growth and urbanization is regarded as the main reason resulting in significant incision of the river channel (Zhang *et al.* 2011). Growing requirements of building materials is stimulating extensive in-channel dredging and sand mining. During 1984–1999, the total amount of sand removed from the river channel was about 17.6 times more than the annual sediment deposition and about 120 times more than the total suspended sediment transport of the Pearl River (Luo *et al.* 2000). Extensive sand dredging has triggered a serious imbalance between depositing and scouring and serous downcutting of the riverbed. A study by Luo *et al.* (2007) indicated that from 1986 to 2003, about 0.87 billion cubic meters of sand was excavated, which caused an average downcutting depth of 0.59–1.73, 0.34–4.43 and 1.77–6.48 m in the main channels of the West River, North River, and East River, respectively, the major water systems in the PRD. From the study by Luo *et al.* (2007), one can see that the magnitude of downcutting of the river channel in the East River is the largest, about 1.77–6.48 m, which has greatly altered the stage–flow relation. Our previous investigation also indicated that the downcutting of the river channel is the major cause of hydrological alterations in the lower Pearl River basin, specifically the PRD (e.g., Zhang *et al.* 2009b, c). The stage–streamflow relation of the Boluo station changed in the late 1990s. On the other hand, after 1992, the stage–streamflow relation of the Sanshui station, an important hydrological station in the Pearl River basin, also changed (Chen & Chen 2002). The similar hydrological alteration times indicate that the beginning of the 1990s was a crucial and sensitive period in the Pearl River basin.

We generally observed decreasing annual maximum water level in the seaward region of the lower Pearl River basin, characterized by decreasing frequency in occurrence of higher annual maximum water level (Zhang *et al.* 2010b). However, the enlarging river cross section area due to downcutting could greatly benefit an increasing concentration of flood flow and reduce the floodplain retention, and hence increasing flood hazard (Zhang *et al.* 2010b), and this point was well evidenced by previous studies (e.g., Lu *et al.* 2007; Chen *et al.* 2009). However, the lower East River is populous with a highly developed socio-economy. The concentration of flood flow and increasing flood hazard may enhance the risk of loss of economy and human life. This can be the negative effect of downcutting in the lower East River basin. As well, the East River bears the prominent responsibility of being the major water supply for mega-cities within the PRD and also for Macau and Hong Kong. The East River provides the water supply for about 80% of Hong Kong's annual water demand (Chen 2001). Decreasing water level, e.g., an abrupt decrease of the water level after the early 1990s, may negatively influence the withdrawal of freshwater from the lower East River basin. The standing water intake should be lowered to make it reach the decreasing water level with the aim of satisfying the freshwater withdrawal.

CONCLUDING REMARKS

In this study, we analyze flow regimes defined by high flow, low flow, mean flow and corresponding water levels. Moreover, the geometric shapes of the river channel cross section are also investigated to determine alterations in flow regimes. The following conclusions can be drawn from this study:

1. Different characteristics are identified for changes in flow and water level. Low flow is increasing, particularly after the early 1990s and high flow is decreasing. Low water level is observed increasingly in the upper East River basin, but is slightly increasing in the lower East River. High water level and mean water level are consistently decreasing from the upper to the lower East River basin. The water level changes show distinctly different features when compared to those in the upper East River basin. An abrupt decrease in the water level at the Boluo station is observed after the early 1990s.
2. Strong stage–flow relation is observed at the Lingxia station. However, the stage–flow relations are poor and even no fixed stage–flow relations can be identified at the Heyuan and Boluo stations; it is particularly the case for the stage–flow relation during low flow periods. The stage–streamflow relation at the Boluo station is strong before the 1990s and is heavily contaminated after the 1990s.
3. Evident changes in the bedform morphology at the Heyuan and the Boluo stations can be identified. Generally, the bedform morphology is relatively stable during low flow periods but is subject to large magnitude changes in high flow periods, e.g., June, which should be attributed to higher hydrodynamic energy of high flows in the flood season than in the dry season, e.g., March and April. However, large magnitude changes in the bedform morphology are still evident at the Boluo station during low flow periods. Alterations in the bedform morphology at the Boluo station can be attributed to downcutting of the river channel as a result of sand mining. The time when the abrupt decrease in water level occurs at the Boluo station is in line with significant hydrological alterations occurring in the upper PRD, which can be largely attributed to downcutting as a result of sand dredging in the upper PRD.
4. Abnormal downcutting due to sand dredging results in altered stage–flow relations. An abrupt decrease in water level at the Boluo station is mainly the result of rapid downcutting in the lower East River basin. Great importance should be attached to the negative effects of downcutting of riverbed and lowering water level in the lower East River basin. Generally, the lowering water level may make human withdrawal of freshwater difficult. Also, enlarged cross sections due to riverbed downcutting may benefit increasing concentration of flood flow and reduce the floodplain retention, and hence increase the risk of flood hazards. Thus, conservation of bedform morphology and mitigation of the adverse consequences of unusual downcutting of riverbeds should be given high priority in the fluvial management and also in water resources management.

ACKNOWLEDGEMENTS

This work is financially supported by the National Natural Science Foundation of China (Grant No. 41071020; 50839005), the Project from Guangdong Science and Technology Department (Grant No. 2010B050800001; 2010B050300010) and by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. CUHK405308). Our cordial gratitude should also be extended to the editor, Dr Dan Rosbjerg, and two anonymous reviewers for their professional and pertinent comments which are greatly helpful for further improvement of the quality of this paper.

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First received 12 December 2011; accepted in revised form 7 June 2012. Available online 22 November 2012