Human-induced hydrological changes in the river network of the Pearl River Delta, South China

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Abstract With the rapid socio-economic development and urbanization, dramatic changes of the hydrological characteristics have taken place in the river network of the Pearl River Delta (PRD) over the past decade. These changes can be mainly attributed to the combined effects of the following human activities: sand dredging in the river, reclamation of former flood-afflicted areas, connection of dykes, construction of numerous bridges, docks and sluices along the river and irrational regulation of water locks. Human activities, along with strong riverbed scouring and sea level rise, respectively, give rise to riverbed degradation and stage reduction in the upper river reaches of the Delta, but sedimentation and tidal backwater resistance in the river mouths. Corresponding to the stage changes, the stage–discharge relationship has been substantially modified, as evidenced by over 2-m drop of stage for the same amount of discharge in some river sections. The ratio of flow partition in river network of the PRD has also been changing continuously in recent years. This is an excellent indication of an increasingly larger portion of flow discharging from the Xijiang River channels into the river network of the Delta, which was found to be the main cause making the inner part of the PRD more and more vulnerable to flood in recent years.

Keywords human activity; hydrological change; Pearl River Delta; river network

INTRODUCTION

Three rivers (Xijiang, Beijiang and Dongjiang, literally West, North, and East River) join together and form the Pearl River Delta (PRD) covering an area of 26 820 km² (Fig. 1).

The crisscross river network (density: 0.68–1.07 km km⁻²) in the PRD is one of the most complex deltaic drainage systems in the world. There are 424 cities and towns with a population of over 10 000 each in the region, including major cities such as Hong Kong, Macau and Guangzhou. The average distance between towns and cities is less than 10 km. In the past two decades, the population of the region has doubled and GDP has increased by more than 10 times. On less than 0.5% area of the Chinese territory, the region sustains about 4% of the population and produces about 20% of the national GDP (including Hong Kong and Macau). However, the rapid economic development and urbanization in the PRD have brought about dramatic changes in hydrological characteristics in this region over the past decade.

Generally, change in hydro-environmental characteristics may be caused by natural factors such as climatic change, and by human activities such as land use
alteration (Li, 1999). It is hard to determine which factor is decisive because all factors may interact (Wen, 1998). However, a previous study has found that both climate change and human activities had caused hydrological changes in the river network of the PRD (Chen, 2000). Climate change, which has been well documented (Gleick, 1986; Guo & Liu, 1997), can change the state of water cycle and cause sea level rise. The influence exerted by human activities has been found out to be more intensive and concentrated.

In the previous studies, more consideration was given to the hydrological responses of urbanization and the change of runoff due to reservoir operation. Few efforts have been made to investigate the changes of the whole hydrological system caused by the complex human activities. As pointed out by the Committee on American River Flood Frequencies (1999), there are very few records about the effects of man’s impact on flood quantity and frequency.

In the Mississippi River, human activities such as the removal of snags and dike construction for flood control, started in 1824. Afterwards, for the purpose of improving navigation, projects of channel constriction and river cut-off were put into
practice. Then as a result, the stage, velocity, stage–discharge relationship and river geomorphic features, all changed in the middle and lower reaches of the Mississippi. Stevens et al. (1975) compared the river topographic maps in 1821, 1888 and 1968, and analysed the man-induced changes in channel dimensions using the 1843–1973 long-term data of level, discharge and river section at the St Louis Station. The results showed that human-induced changes of level, discharge and river section had a clear division between the 19th century and 20th century in accordance with the intensity of engineering work.

In particular, Biedenharn & Watson (1997) analysed the effects of river cut-off in the 970-km river reach of the Mississippi from Columbus to Natchez. Using specific gauge records and peak stage–peak discharge plots for the time period 1950–1994, they documented the stage adjustments in the lower Mississippi River during the pre-cut-off (1880s–1930s) and post-cut-off (1943–1994) periods. Also employing the specific-gauge technique, Pinter et al. (2001) used daily stage and discharge data of three gauges in the middle Mississippi to calculate a rating regression for each year and track stage changes associated with fixed discharge values. Considering the tendency of stage change, they recalculated the flood frequency in the middle Mississippi, and obtained a different result showing that the recurrence interval of peak stage at the St Louis station in 1993 was less than 100 years, much lower than that of the previous calculations. Through water balance calculation in the Republican River basin, Szilagyi (2001) found that mean runoff of this basin in the period 1977–1996 was reduced by 40% from that in the period 1949–1968. In this study, it was revealed that the runoff reduction was not only the contribution of hydro-meteorological changes but mainly a result of human activities such as reservoir building, farm irrigation, vegetation alteration and water and soil conservation.

It was also found from the previous research work (Xu, 1998; Chen, 2000; He & Han, 1998; Li, 2001) that the hydrological characteristics of the PRD had a significant change around 1992. This kind of change (Fig. 2), is a result of the evolution of over 100 years in developed countries, occurring within a period of only several years in the PRD. Until the early 1980s most channels in the PRD had maintained a balance between erosion and sedimentation or experienced a slight net deposition. However, since the mid- and late-1980s, most upstream channels have been incised, leading to faster and larger channel discharge. Associated with sea level rise and the resistance due to tidal surges, sedimentation has occurred in some channel sections near the river outlet.

![Fig. 2 Hydrological changes in the PRD under natural and human activities.](image-url)
River channels extend faster and faster into the estuary and the South China Sea. Enlargement and connection of scattered and small embankments, together with construction of sluice gates, give rise to the reduction of the water surface area and concentration of flow into major channels which generally cause stages to go up slightly. The continuous rise of water levels in the inner part of the PRD has brought about serious flood threats in recent years.

This paper aims to illustrate a variety of human-induced hydrological changes in the PRD river network and to present an analysis of the causes and effects of these changes.

HYDROLOGICAL CHANGES IN THE PRD RIVER NETWORK

Changes of stage

Stages in the PRD river network changed significantly during the past several decades. From the early 1950s to the 1980s, stages increased slightly, particularly during the low tide period (Table 1). Since the early 1990s, stage in the upper part of the PRD has dropped significantly while the opposite situation has become more common in the central PRD.

For example, at Sanshui station, the key station on the Beijiang River at the entrance to the PRD (Fig. 1), stage dropped by 3 m for similar or identical discharges, between 1990 and 1998. Under median and low levels of below 7 m at Sanshui, the change of hydrological elements is even more significant; for the same stage the corresponding discharge in 1998 increased by 3000 m$^3$s$^{-1}$ to 4000 m$^3$s$^{-1}$, about 50% to 100% of that in 1992 (Fig. 3). Changes of stage associated with very similar discharges at four river gauges in the upper part of the PRD are shown in Table 2.

In Shunde and Panyu, two counties located in the central PRD, recurrence intervals of flood stage for the same events have been very different from the upper PRD since the early 1990s. For example, stages in Shunde and Panyu exceeded 200-year records during the 50-year flood of the Xijiang and Beijiang rivers in June 1994 (see Table 3), and the return period of the high tidal levels in Nansha and Wanqingsha, the two tide stations in the mouth of the Beijiang River, was only about 5-years in the same period. The highly inconsistency of flood frequencies in the river network is surely an indication of changes in the hydrological system.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Tide</th>
<th>1950s</th>
<th>1960s</th>
<th>1970s</th>
<th>1980s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baijiao</td>
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<td>0.41</td>
<td>0.38</td>
<td>0.44</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Low tide</td>
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<td>−0.43</td>
<td>−0.56</td>
<td>−0.57</td>
</tr>
<tr>
<td>Lanshi</td>
<td>High tide</td>
<td>0.56</td>
<td>0.57</td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>Low tide</td>
<td>−0.41</td>
<td>−0.41</td>
<td>−0.34</td>
<td>−0.33</td>
</tr>
<tr>
<td>Rongqi</td>
<td>High tide</td>
<td>0.55</td>
<td>0.54</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Low tide</td>
<td>−0.43</td>
<td>−0.41</td>
<td>−0.39</td>
<td>−0.36</td>
</tr>
<tr>
<td>Wanqingsha</td>
<td>High tide</td>
<td>0.56</td>
<td>0.53</td>
<td>0.59</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Low tide</td>
<td>−0.68</td>
<td>−0.7</td>
<td>−0.66</td>
<td>−0.64</td>
</tr>
</tbody>
</table>
Changes in the stage-discharge relationship

Since the early 1990s, even greater changes of stage (or discharge) under the same grade of discharge (or stage) have taken place in some river reaches of the PRD. Due to the lowering of the riverbed, the stage-discharge curve has shifted to the right at many locations, and the stage often decreases more at smaller discharges. The yearly
stage–discharge relationships from 1953 to 1998 at Sanshui are shown in Fig. 3. Since 1992, stage has dropped to varying extents at Sanshui Station (Table 4).

Changes in the flow partition ratio

Distribution of river flow among most river branches in the PRD has also changed significantly. Figure 4 shows a clear downward trend since 1953 for the discharge partition ratio between Makou and Sanshui, the two key stations at the entrance of the PRD, with a steady increase in discharge at Sanshui Station. The same situation was found in the central PRD; the flow partition ratio of Tianhe Station/Nanhua Station dropped from 56.5/43.5 in the 1970s to 53/47 in the mid 1990s. The increase of flow partition from the Xijiang River to the central PRD has directly caused the rise of stage and thus the flood hazards in this area.

![Fig. 4 Changes of the flow partition ratio between Sanshui and Makou.](image)

CAUSES OF THE CHANGES IN HYDROLOGICAL CHARACTERISTICS

Sand dredging in channels

Along with the rapid development of urbanization and reclamation, large-scale sand dredging in the river network of the PRD started in the mid 1980s and reached its climax in the early 1990s. Based on the estimated amount of sand used for construction and reclamation in the PRD (with the sand used for the construction of Macau Airport and Hong Kong Airport taken into account), since 1985 the amount of
dredged sand has been $500-600 \times 10^6$ m$^3$ in the Delta of the Xijiang River and Beijiang River (Luo & Luo, 2000), the majority of the PRD. The total amount in recent 15 years was $760 \times 10^6$ m$^3$. This is the direct cause of riverbed drop (usually 3–8 m) in the upper part of the PRD.

The area under the largest influence of sand dredging in the Dongjiang delta (the eastern part of the PRD) is the section from Boluo to Shilong, the lower reach of the Dongjiang River, where the riverbed has mostly been scoured with an incision depth of 6–9 m. Zhao & Deng (2001) compared the TM and SPOT satellite images of 1988 against those acquired in 1990, 1993, 1995 and 1997. It was found that in 1988 there were about 71 pieces of sandbar and flood land in the section between Boluo and Zengjiangkou along the Dongjiang River with an area of more than 400 m$^2$ above the water surface. Of these, some have now disappeared and about 46 sandbars and jutting flood land are below the water surface in the satellite imagery from after 1988. The total amount of dredged sand from this section is up to $6.61 \times 10^6$ m$^3$ in the 9-year period from 1988 to 1997.

Such a large amount of sand dredged from the river network absolutely cannot be recovered by natural sedimentation in a short period of time. Taking the 87-km river section from Sixianjiao to Baiqintou on the mainstream of the Xijiang River as an example, the natural sedimentation amount in the years from 1992 to 1997 was approximately $5.54 \times 10^6$ m$^3$ in this section, whereas the amount of dredged sand during this period was $147.7 \times 10^6$ m$^3$, which is equivalent to the amount of natural sedimentation over 160 years. Therefore, sand dredging in rivers (Fig. 1) is a key factor in the riverbed evolution and corresponding changes of stage and stage–discharge relationship in the PRD over the past 10 years.

Reclamation and connection of dykes

Large-scale connection of dykes was carried out in the 1960s and 1970s in the PRD. More than 20,000 dykes were combined into over 400 dykes (see the major dykes in Fig. 1). Sixteen branches were blocked by water locks, reducing the 1600 m width of the discharge water surface. Dyke connections blocked or controlled some branches of flood division rivers, which actually weakened the ability to mitigate the flood and store storm water, and led to the concentration of floods (especially the violent and median ones) into the main channel which resulted in the increase of flood discharge in the main river courses and the continuous rise of flood stages. After dyke connection, relative to 1953, stage at stations in the lower reaches of the Beijiang River gradually went up, reaching a climax during 1959 and 1962, and then decreased year after year since then in association of riverbed adjustment. Stages declined nearly to their original state in the 1970s.

Bridge construction and use of flood land

In 1988 there were only 61 bridges over the main channels in the PRD but the number of bridges reached 216 by 1998. Among the 155 new bridges, 142 were built in the Xijiang and Beijiang river network and 62 are located in the inner part of the Delta.
Many bridges were only several kilometres away from each other. Generally the piers make up over 5% of the river discharge area, which could bring about dammed water of 10–20 cm depth, and 65 cm at the maximum. For channels with a width of less than 300 m, the dammed water caused by piers can slow down the flow across the whole section while resistance forces between the two piers can accelerate the flow and therefore part of the riverbed may be scoured. On the other hand, it was a common case that the flood land of the river network was occupied for different land use purposes. Compared with the 1977, fish ponds, architectural complexes and other permanent buildings with an area of more than $10^6$ m^2 were added along the Shunde channel in 1994. Changes in the morphology of the flood land caused the rise of the stage.

**Sea level rise**

Besides the fact that climate is getting warmer, the rise of the sea level is mainly engendered by diastrophism, the compressed sediment at the estuary, recent fracture activities, earthquakes and hydrological and geomorphic factors (Zeng & Qiu, 1994). Huang *et al.* (1999) predicted that, from 1990 to 2030, the relative rise of sea level at the mouth of the Pearl River would consist of four parts: (a) the absolute rise of sea level would be 8 cm (with a rate of 2.0 mm year$^{-1}$); (b) the abnormal rise of relative sea level would be 6.4–12.1 cm; (c) the high tide level would rise 2–5 cm over the sea level in accordance with a 30 cm rise of sea level; and (d) the relative sea level rise due to subsidence would be 6–8 cm (with the rate of 1.5–2.0 mm year$^{-1}$). These four components combine to indicate that the relative sea level at the mouth of the Pearl River could rise in total by 22–33 cm.

When the sea level at the river mouth rose by 30 cm, it was calculated that the tidal station near the river mouth was influenced most with a stage rise range of 20–30 cm; next the tidal station near Humen experienced a stage rise range of 5–15 cm. The station at the middle stream of the Xijiang River, which is at the middle and upper part of the PRD, was the least influenced with an almost zero stage rise range.

**CONCLUSIONS**

Over the past five decades or so, particularly the recent 10 years, tremendous changes have occurred in the hydrological characteristics of the PRD river network; these are due to rapid social and economic development and can be generally classified into the following three phases.

(a) In the 1960s up to the mid-1970s, stages of the major river courses rose continuously and the whole hydrological characteristics experienced a sudden change, as the consequences of large-scale reclamation and connection of dykes, reduction of flood storage capacity and concentration of violent flood to the main channel.

(b) In the late 1970s and early 1980s, large-scale dyke connection was almost completed. The dynamic system of the river courses was restructured and stages regressed and stayed stable for a short period of time.
(c) Since the mid-1980s, the rapid social and economic development, treatment of river courses and outlets, sand dredging in rivers and large scale construction of docks and bridges, have all contributed to changes in the hydrological characteristics in the river network of the PRD. Stages of major river courses in the upper part of the PRD fell while the hydraulic slope and flow velocity increased. Sand bars in the river mouth grew with the rising sea level and tidal backwater at estuaries. The threat of flood hazards increased in the inner areas because of the rising flooding level, which is due to the dammed water formed by pressure on the water body from both the upper and lower river reaches in the region.

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