Variability of water levels and impacts of streamflow changes and human activity within the Pearl River Delta, China

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Variability of water levels and impacts of streamflow changes and human activity within the Pearl River Delta, China

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Abstract The Pearl River Delta (PRD) is a complicated criss-cross river network. The booming economy and intensifying human activity have greatly altered the natural water levels, which threatens regional sustainable development. The Mann-Kendall trend test and the kriging interpolation method were used to detect the spatial and temporal patterns in the trends of extreme high/low water levels related to different magnitudes of streamflow, in order to explore the impacts of hydrological processes on the water-level changes throughout the PRD. The results indicate that: (a) streamflow changes at the Sanshui and Makou stations exhibit different characteristics. No significant trend can be identified in the streamflow changes at Makou station; however, the streamflow at Sanshui station shows a significant increasing trend, especially in low-flow periods. The decreasing Makou/Sanshui streamflow ratio exerts tremendous impacts on the water-level changes in the hinterland of the PRD region. (b) Extreme high/low water levels exhibit similar changing patterns. The extreme high/low water levels in the high/normal flow periods are decreasing in both the upper PRD and the hinterland of the PRD region. Increasing extreme high/low water levels in low-flow periods can be identified in the hinterland of the PRD region. The coastal regions are characterized by increasing extreme high/low water levels. (c) Extreme high/low water levels for high/normal flow periods in the hinterland of the PRD are heavily impacted by topographic changes due to in-channel dredging. Increasing extreme high/low water levels along the coastal regions are mainly backwater effects caused by serious siltation and rising sea level. This study has scientific and practical merits in regional fluvial management and mitigation of natural hazards.

Key words Mann-Kendall trend test; streamflow processes; human activity; water-level variability; Pearl River Delta

Variabilité des hauteurs d’eau et impacts des changements de débit et des activités humaines dans le Delta de la Rivière des Perles, Chine

Résumé Le Delta de la Rivière des Perles (DRP) est un réseau hydrographique entrecroisé complexe. L’économie florissante et l’intensification des activités humaines ont grandement altéré les hauteurs d’eau naturelles, ce qui représente une menace pour le développement durable régional. Le test de Mann-Kendall pour les tendances et la méthode d’interpolation de krigeage ont été utilisés pour détecter les patrons spatio-temporels dans les tendances des niveaux d’eau extrêmes supérieurs/inférieurs en relation avec différentes magnitudes de débit, de façon à explorer l’impact des processus hydrologiques sur les changements du niveau de l’eau à travers le DRP. Les résultats indiquent que: (a) les changements de débit aux stations de Sanshui et de Makou présentent des caractéristiques différentes. Aucune tendance significative ne peut être identifiée dans les variations de débits à Makou; alors que les débits à Sanshui montrent une tendance à la hausse significative, particulièrement pour les périodes d’étiage. Le rapport décroissant entre les débits à Makou et ceux à Sanshui exerce un impact intense sur les variations de hauteur d’eau dans l’arrière-pays du DRP. (b) Les niveaux d’eau extrêmes supérieurs/inférieurs présentent des patrons changeants similaires. Les niveaux d’eau extrêmes supérieurs/inférieurs pendant les périodes normales ou de crue diminuent à la fois dans la partie amont du DRP et dans son arrière-pays. Des niveaux d’eau extrêmes supérieurs/inférieurs en hausse pendant les périodes d’étiage peuvent être identifiés dans l’arrière-pays du DRP. Les régions côtières sont caractérisées par une hausse des niveaux d’eau extrêmes supérieurs/inférieurs. (c) Les niveaux d’eau extrêmes supérieurs/inférieurs pour les périodes normales ou de crue dans l’arrière-pays du DRP sont fortement impactés par les changements topographiques dus au dragage dans les cours d’eau. Les niveaux d’eau extrêmes supérieurs/inférieurs en hausse le long des régions côtières sont principalement des effets de contrôle aval causés par une sédimentation sévère et
INTRODUCTION

River deltas worldwide provide numerous ecological and economic benefits and are usually densely populated (Pont et al., 2002; Ericson et al., 2006). Due to their unique and exceptionally important role in the development of human society, river deltas are receiving increasing attention from hydrologists, fluvial geomorphologists and policy makers. Belt (1975) suggested that the progressive constriction of the Mississippi River, USA for navigation since 1837 has caused bottom erosion in some stretches, as the combination of navigation works and levees causes significant rises in the flood stage. Milliman et al. (1989) estimated the land loss based on estimates of the eustatic sea-level rise, natural subsidence, and accelerated subsidence in the Nile and Bengal deltas, indicating that, under a worst-case scenario, habitable land loss in Egypt and Bangladesh between 1989 and 2100 could be 24% and 36%, respectively. Bott et al. (2006) investigated morphologic changes of the Mersey Estuary (located in northwest England) using historical trend analysis and expert geomorphological assessment, suggesting that the estuary experienced major changes over the last 150 years, notably between the late 19th century and 1950.

The criss-cross river network with a density of 0.68–1.07 km/km² in the Pearl River Delta (PRD) is one of the most complicated deltaic drainage systems in the world (Chen & Chen, 2002). The PRD has a dense agglomeration of over 100 towns and cities, being the fastest developing region in China since the country adopted the “open door and reform” policy in the late 1970s. The highly developed social economy puts tremendous pressure on the local environment, and makes the PRD vulnerable to natural hazards, such as flood, salinity intrusion and storm surge. During recent years, engineering facilities have been designed for flood protection and to cater for the huge demand for building materials. After the mid 1980s, intensive channel dredging, sand mining and levee construction, etc., resulted in a manmade increase in flood stage and frequent flood hazards within the PRD (Zeng et al., 1992; Liu et al., 2003).

The salinity intrusion, frequent floods, rising sea level as well as water pollution are key factors affecting the sustainable development of the PRD. A large amount of research about the water levels and possible causes can be found in the Chinese literature (e.g. Zeng et al., 1992; Huang et al., 2000; Luo et al., 2000; Yang et al., 2002; Liu et al., 2003; Chen et al., 2004). Several research projects have suggested that hydrological changes to the PRD occurred after about 1992 (Chen & Chen, 2002); however, different changing patterns can be identified at individual stations in the PRD (Yang et al., 2002). The river channel in the PRD was greatly altered due to in-channel dredging and levee construction after about the mid-1980s, resulting in a decrease in the water level (Lu et al., 2007). The rising sea level in the estuary leads to an obvious backwater effect, which, in turn, further forces the flood stage upward (Xu, 1998; Huang et al., 2000). It should be noted that tremendous impact of hydrological events on human society are more likely to accrue through extreme events than through slow changes in the mean conditions (Wigley, 1985). Therefore, public awareness of extreme events has risen sharply in recent years, partly because of the catastrophic nature of floods, typhoons and the rising sea levels (e.g. Beniston & Stephenson, 2004; Zhang et al., 2006a,b). Riverine streamflow from the upper PRD heavily influenced the water levels within the PRD river network (Huang & Zhang, 2004). Furthermore, different combinations of streamflow and water levels may directly impact the flood stages and salinity intrusion. Previous research is helpful for understanding the changes in water level and their possible causes in the study region. However, previous research only focused on certain facets of water-level changes (e.g. Zeng et al., 1992). Extreme water levels have not yet been studied. An integrated study based on updated data sets and using robust methodology is necessary for a better understanding of the spatial patterns of extreme water levels across the PRD. Therefore, the objectives of this paper are: (1) to detect trends in the extreme high water level (EHWL) and extreme low water level (ELWL) under different magnitudes of streamflow; and (2) to explore the spatial patterns of the trends in extreme water levels related to different magnitudes of streamflow and possible impacts from human activities within the PRD. This study will be of scientific and practical merit for the local water resource management and the mitigation of floods.
sea-level rise, and salinity intrusion, under the changing environment in the Pearl River Delta.

**DATA**

A data set of extreme high/low water levels covering 1958–2005 was collected from 22 gauging stations within the PRD (see Table 1). The hydrological data before 1989 are extracted from the *Hydrological Year Book* (published by the Hydrological Bureau of the Ministry of Water Resources of China) and those after 1989 were provided by the Water Bureau of Guangdong Province. The location of the gauging stations can be seen in Fig. 1. The missing data were filled in, based on the data of neighbouring stations, using the regression method with the determination coefficients $R^2 > 0.8$ and even, in some cases, $R^2 > 0.95$. To characterize changes in water level related to river streamflow, daily streamflow data were collected at the Makou and Sanshui stations, two upstream stations controlling the water level in the PRD. The following steps were taken before further analysis: (1) the maximum/minimum streamflow of a time interval when the extreme high/low water level occurred was singled out; (2) the selected streamflow and associated extreme high/low water level were classified based on the magnitude of the streamflow. Herein, high, normal and low streamflow was taken as the streamflow exceeding mean $+0.5$ SD, between mean and below mean $–0.5$ SD (SD: standard deviation) of the maximum/minimum streamflow series, respectively (Yoo, 2006). Extreme high/low water levels in relation to high, normal and low streamflow were analysed in the current study.

**METHODS**

The Mann-Kendall trend test (Mann, 1945; Kendall, 1975) is regarded as a powerful tool for exploring trends in hydrological series (Van Belle & Hughes, 1984; Yu et al., 1999). This test has the advantage of not assuming any distribution form for the data and has similar power to its parametric competitors (Serrano et al., 1999). Therefore, it is highly recommended for general use by the World Meteorological Organization (Mitchell et al., 1966). The 95% confidence level was accepted to evaluate the significance of the trends. The extreme high/low water level related to high, normal and low streamflow series were regarded as being independent. If not, the effect of the serial correlation on the Mann-Kendall (MK) test was eliminated using the pre-whitening technique (Yue & Wang, 2002). Therefore, the Mann-Kendall method was considered to be suitable for the analysis.

To estimate unmeasured values at any point across the PRD region, geostatistical or stochastic

<table>
<thead>
<tr>
<th>Station name</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Time interval</th>
<th>Periods with missing data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dasheng</td>
<td>113°32'</td>
<td>23°03'</td>
<td>1958–2005</td>
<td>Jun–Dec 1963</td>
</tr>
<tr>
<td>Denglongshan</td>
<td>113°24'</td>
<td>22°14'</td>
<td>1959–2005</td>
<td>Jan–Sep 1958</td>
</tr>
<tr>
<td>Hengmen</td>
<td>113°31'</td>
<td>22°35'</td>
<td>1959–2005</td>
<td>No missing data</td>
</tr>
<tr>
<td>Huangjin</td>
<td>113°17'</td>
<td>22°08'</td>
<td>1965–2005</td>
<td>No missing data</td>
</tr>
<tr>
<td>Huangpu</td>
<td>113°28'</td>
<td>23°06'</td>
<td>1958–2005</td>
<td>No missing data</td>
</tr>
<tr>
<td>Laoxyang</td>
<td>113°12'</td>
<td>23°14'</td>
<td>1958–2005</td>
<td>Dec 1959</td>
</tr>
<tr>
<td>Nanhua</td>
<td>113°05'</td>
<td>22°48'</td>
<td>1958–2005</td>
<td>No missing data</td>
</tr>
<tr>
<td>Nansha</td>
<td>113°34'</td>
<td>22°45'</td>
<td>1963–2005</td>
<td>No missing data</td>
</tr>
<tr>
<td>Rongqi</td>
<td>113°16'</td>
<td>22°47'</td>
<td>1958–2005</td>
<td>No missing data</td>
</tr>
<tr>
<td>Sanduo</td>
<td>112°59'</td>
<td>22°59'</td>
<td>1958–2005</td>
<td>No missing data</td>
</tr>
<tr>
<td>Sanshakou</td>
<td>113°30'</td>
<td>22°54'</td>
<td>1958–2005</td>
<td>1959</td>
</tr>
<tr>
<td>Sanshui</td>
<td>112°50'</td>
<td>23°10'</td>
<td>1958–2005</td>
<td>Sep–Dec 1959; 1960</td>
</tr>
<tr>
<td>Shilong</td>
<td>113°51'</td>
<td>23°07'</td>
<td>1980–2005</td>
<td>No missing data</td>
</tr>
<tr>
<td>Sishengwei</td>
<td>113°36'</td>
<td>22°55'</td>
<td>1958–2005</td>
<td>1964</td>
</tr>
<tr>
<td>Tianhe</td>
<td>113°04'</td>
<td>22°44'</td>
<td>1958–1988</td>
<td>No missing data</td>
</tr>
<tr>
<td>Zhuyin</td>
<td>113°17'</td>
<td>22°22'</td>
<td>1959–2005</td>
<td>No missing data</td>
</tr>
</tbody>
</table>
methods are preferred to be used in spatial interpolation. Goovaerts (1999) indicated that the major advantage of the kriging method over other simpler methods is that sparsely sampled observations of the primary attribute can be complemented by secondary attributes that are more densely sampled. Moreover, the kriging method has already been applied in exploring the spatial patterns of water levels over the PRD region (Chen et al., 2004; Zhang & Chen, 2004). Therefore, the kriging interpolation method was used in the study to demonstrate the spatial distribution of the MK trends in water levels within the PRD region with the help of the Surfer® software package.

RESULTS

Extreme high water level (EHWL)

Figure 2 demonstrates the spatial distribution of the MK trend in EHWL in high-streamflow periods (Fig. 2(a)), normal-streamflow periods (Fig. 2(b)) and low-streamflow periods (Fig. 2(c)). Figure 2(a) illustrates that Xi’nantong, Shunde, North River, upper West River, Dongping Channels and part of the North mainstream of East River are characterized by significant decreasing EHWL in high-streamflow periods. Significant increasing EHWL can be identified in the Modaomen, Hengmen and Hongqimen Channels.
Fig. 2  The MK trend of the extreme high water level (EHWL) during (a): high-streamflow periods; (b) normal-streamflow periods and (c) low-streamflow periods. Solid lines denote increasing trend and dashed lines – decreasing trend. The thick lines show the significant MK trend at >95% confidence level. Triangles denote the gauging stations.
(Figs 1(a) and 2(a)). The river channels characterized by significant decreasing high water level (Fig. 2(a)) are usually those also characterized by highly intensive dredging, e.g. Dongping Channel (Fig. 1(b)). It seems that in-channel dredging exerts more influence on the water level than the streamflow does. The coastal regions, especially Modaomen, Hengqimen and Hengmen Channels, are characterized by significant increase in water level in the high-streamflow periods. Moreover sand dredging was being carried out in some channels of the coastal regions, e.g. Shiziyang Channel, Yamen Channel, Jiaomen and Honggimen (Fig. 1(b)), which will have had an advantageous effect on water levels in these regions. The water levels in the high-streamflow periods of the remaining parts of the PRD show no significant trend. However, it can be seen from Fig. 2(a) that the majority of the PRD is characterized by decreasing EHWLs, and the places in which increasing water levels predominate are mostly identified along coastal regions.

Similar changing patterns of the EHWL in normal-streamflow periods can be identified from Fig. 2(b). Increasing EHWL can be detected along the coastal regions, i.e. the Yamen Channel and the regions along the Laoyagang station–Huangpu station–Sishengwei station reach. The difference is that the area experiencing significant decrease in EHWL is larger in high-flow periods than in normal-flow periods. Therefore, the changes in extreme water levels in the high-/normal-streamflow periods seem to be influenced by similar driving factors. Figure 2(c) demonstrates distinct changing patterns of the EHWL in the low-streamflow periods when compared with those in high-/normal-streamflow periods (Fig. 2(a) and (b)). Most parts of the PRD are characterized by increasing EHWL in low-streamflow periods (Fig. 2(c)). More of the PRD area is characterized by significant increase in EHWL in low-streamflow periods compared to high-/normal-streamflow periods (Fig. 2(a) and (b)). The lower Shunde, mainstream Pearl River, Shawan, south mainstream East River, north mainstream East River, Hengmen and middle Modaomen Channels show significant increase in EHWL in low-streamflow periods. Only the upper West River channel and the Tanjiangiang channel are characterized by decreasing EHWL in low-streamflow periods. Whether in high-flow periods or normal- and low-flow periods, the EHWLs along the coastal regions are increasing.

**Extreme low water level (ELWL)**

Figure 3 demonstrates the spatial patterns of the ELWL in high-streamflow periods (Fig. 3(a)), normal-streamflow periods (Fig. 3(b)) and low-streamflow periods (Fig. 3(c)). Figure 3(a) indicates that the majority of the PRD is characterized by decreasing ELWL in the high-flow periods. The ELWL in the North River, the Dongping, and the Xi’nyanong Channel has a significant decreasing trend. The coastal regions are characterized by increasing ELWL in high-streamflow periods (Fig. 3(a)). Specifically, the ELWLs in the Hengmen, Hengqimen and Humen Channels show a significant increasing trend. The Xi’nyanong, the North River, and the Dongping Channel feature a significant decreasing ELWL (Fig. 3(a)). Most parts of the PRD are characterized by a decreasing trend in terms of ELWL in normal-streamflow periods (Fig. 3(b)), except for the south mainstream East River. A significant decreasing trend in the ELWL can be identified in the majority of the PRD region. Considering Figs 1(b), 3(a) and 3(b), we find that the areas dominated by decreasing ELWL correspond well to those characterized by highly-intensive and moderate in-channel dredging, demonstrating the tremendous impact of in-channel dredging on water levels within the PRD region. Figure 3(c) shows the changing trends in ELWL in the low-streamflow periods. It can be seen from Fig. 3(c) that increasing ELWL can mainly be identified along the coastal regions and in the area covered by Laoyagang, Huangpu, Dasheng and Sishengwei stations. However, a significant increasing trend in the ELWL in low-streamflow periods can be found mainly along the north mainstream East River, the middle Modaomen channel, the Honggimen and the Hengmen. Decreasing ELWL is detected in the North River, upper Dongping, West River, Shawan and Tanjiangjiang channels, but it is not significant at >95% confidence level (Fig. 3(c)). During January–April and in November and December, the streamflow at Sanshui station shows a significant increasing trend in comparison with streamflow changes for May–October, which, together with increasing Sanshui/Makou streamflow ratio, lead to the increasing water level in the hinterland of the PRD in low-flow periods.

**Streamflow changes**

The changes in the water levels throughout the PRD are heavily influenced by hydrological processes in the upper PRD (Peng et al., 2004; Zhang & Chen,
Fig. 3 The MK trend of the extreme low water level (ELWL) during (a) high-streamflow periods; (b) normal-streamflow periods, and (c) low-streamflow periods. Solid lines denote increasing trend and dashed lines – decreasing trend. The thick lines show the significant MK trend at >95% confidence level. Triangles denote the gauging stations.
Therefore, we addressed the hydrological properties of the Makou and Sanshui stations. Then we analysed the correlation between hydrological variations and water-level changes, to demonstrate the influence of streamflow variations on water-level changes across the Pearl River Delta. The West River is the largest river system of the Pearl River basin with a length of 2214 km and a drainage area of 353 120 km², accounting for 77.8% of the total area of the Pearl River basin. The North River is the second largest river (length: 468 km, drainage area: 46 710 km², accounting for 10.3% of the total basin area); and the East River is the third largest river (drainage area: 35 340 km², accounting for 7.8% of the total basin area). The Makou and the Sanshui stations are the key gauging stations for detecting discharge into the West River Delta and North River Delta, respectively. The annual mean streamflow at Makou station is about four times that at Sanshui station (1959–2005).

Figure 4(a) indicates that high-flow periods are from May to August and low-flow periods from October through to March. Figure 4(a) also shows that the ratio of Makou/Sanshui streamflow was greater in winter and smaller mainly in May and June. Figure 4(b) shows that the streamflow at Makou station in February, March and July is increasing and in the remaining months it is decreasing (but it is...
not significant at $>95\%$ confidence level). More distinct decreasing streamflow can be identified in August–December. However, the streamflow at Sanshui station has shown a significant increasing trend, except in August. The streamflow in winter and spring shows a more significant trend when compared with other seasons (Fig. 4(c)). Figure 4(d) illustrates the decreasing monthly total streamflow at these two stations for August–December, April and May, and increasing values for January–March, June and July. It should be noted that the Makou/Sanshui streamflow ratio shows a significant decreasing trend, indicating that streamflow allocation resulted in greater streamflow at the Sanshui station (Fig. 4(e)). The streamflow changes at Makou and Sanshui stations are directly influenced by precipitation changes in the West River basin and the North River basin, respectively. Wang et al. (2006) indicated that the upper West River basin is characterized by decreasing precipitation, especially in summer and autumn. However, increasing precipitation is observed in the North and the East River basins. The summer precipitation in the North River basin is decreasing. Discharge of the West River is decreasing and that of the North River (Shijiao station) is increasing (Zhang et al., 2007). These findings further corroborate the streamflow changes at Makou and Sanshui stations.

**Correlation between streamflow and water levels**

To further investigate the impacts of the hydrological processes in the upper PRD on the water-level changes across the PRD region, we analysed the correlation between streamflow changes at Sanshui and Makou stations and the extreme high/low water levels of the stations in the hinterland of the PRD region. We also mapped the spatial distribution of correlation coefficients with the aim of showing possible influences of distance between hydrological stations and water level stations on the degree of impact of streamflow variations on water level across the Pearl River Delta. We only analysed the correlation between streamflow data of Sanshui and Makou stations and extreme high/low water levels of Sanshui, Makou, Sanduo, Rongqi, Sanshakou, Tianhe, Hengmen and Huangjin because: (1) we aim to mainly explore the high/low water-level changes in the hinterland of the PRD and the selected stations cover the study region well; and (2) the water levels at the latter stations are directly influenced by hydrological processes represented by streamflow changes at Sanshui and Makou stations as opposed to other stations in the Pearl River Delta. Figures 5 and 6 indicate the correlation between the extreme high/low water level and the associated streamflow within the PRD, showing the possible impacts of hydrological processes of the upper PRD on changes in water levels within the PRD.

Figure 5 demonstrates the correlation between high water levels and the related streamflow across the PRD. It can be seen from Fig. 5 that good correlation exists between high water level and related streamflow at both Makou and Sanshui stations ($R = 0.95$ and $R = 0.88$, respectively). The correlation between the high water level at Sanshui station and the related streamflow at Makou station is also good ($R = 0.94$), showing the overwhelming impact of the streamflow at Makou station on the water-level changes at Sanshui station. It is easy to understand due to the fact that the multi-annual mean streamflow at Makou station is four times that of Sanshui station. A good correlation can also be observed for Sanduo, Tianhe and Rongqi stations. In addition, the $R$ value changes with the distance between the studied stations and Makou and Sanshui stations, and is also influenced by the complexity of the river channels between them. For example, Rongqi station is relatively far from Makou and Sanshui stations and there are more criss-cross river channels between Rongqi, Makou and Sanshui stations in comparison with Tianhe station. Therefore, $R$ values for Rongqi station are 0.9 and 0.88; however, the $R$ values for Tianhe station are larger, i.e. $R = 0.94$ and $R = 0.92$. This is further discussed in the next section. Comparatively, poor correlations are identified for Sanshakou, Hengmen and Huangjin stations with $R \leq 0.5$. Huang et al. (1999) classified the PRD regions into three zones based on extreme high tidal levels as 5 cm and 25 cm: tidal-impacted zone; tidal- and flood-impacted zone; and flood-impacted zone (Fig. 1(b)). Smaller $R$ values are identified in the tidal-impacted zone. Therefore the water levels along the coastal regions are impacted by both hydrological processes of the upper PRD and tidal activities. Figure 6 displays similar changes in comparison with Fig. 5. The difference is that the $R$ values for the correlation between ELWLs and associated streamflow are generally smaller than those for EHWLs. The water levels across the PRD are controlled by both streamflow changes and tidal activity. Water levels in the upper PRD are controlled mainly by streamflow changes; those in the hinterland of the PRD – by both streamflow and tidal activities; and those in coastal regions – by tidal
activity (Ou & Yang, 2004). In addition, water levels of the PRD are more impacted by tidal activity in low-low periods than high-flow periods. These are the main causes for the relatively poor correlation between ELWL and the associated streamflow changes in comparison to that between EHWL and the associated streamflow changes.

Figure 7 shows the spatial distribution of correlation coefficients between streamflow variations at hydrological stations (Sanshui and Makou) and the water levels at eight stations, demonstrating changes in correlation with distance between water-level stations and hydrological stations. It can be observed from Fig. 7 that the larger the distance between water-level stations and hydrological stations (Makou and Sanshui), the smaller the correlation coefficient, showing the weakening tendency in terms of influence of hydrological processes of the upper Pearl River Delta on the water-level variations within the Pearl River Delta. Generally, larger correlation coefficients were identified between streamflow variations of Makou station (the West River) and water-level changes when compared to those of Sanshui station (the North River). This is mainly due to larger
streamflow amount of the West River compared to that of the North River.

DISCUSSION

Water-level variations within the Pearl River Delta are the integrated consequences of human activities, such as sand dredging, hydrological processes, and astronomical tidal fluctuations along the Pearl estuary. The results of this study indicate that EHWLs in high-streamflow periods and low water levels in normal-streamflow periods are more impacted by deepened river channels as a result of in-channel sand dredging, and those water-level components in low-streamflow periods are mainly the results of hydrological processes in the upper Pearl River Delta, which leads to distinct spatial patterns of trends in water-level components in high- (normal) and low-streamflow periods. Zhou et al. (2001) indicated that highly-intensive in-channel dredging greatly altered the allocation of streamflow and sediment load within the river channels and also the boundary conditions of the river channel, and this exerted considerable influences on the water-level changes across the Pearl River Delta. A study by Luo
et al. (2007) indicated that, from 1986 to 2003, about $8.7 \times 10^8$ m$^3$ of sand were excavated, which caused average downcutting depths 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. The general decreasing water level within the PRD, but abrupt increase in water level in some specific river channels, may be mainly the result of in-channel dredging, which resulted in serious downcutting of the river channels in the hinterland of the PRD (Zhou et al., 2001; Hou et al., 2004). In the low-streamflow periods, the significantly increasing streamflow at Sanshui station and increasing Sanshui/Makou streamflow ratio can be regarded as the main causes for the significant increase in high water level. We can tentatively conclude that the EHWLs in the high/normal flow periods are mainly influenced by in-channel dredging. The changes in EHWLs in the low-streamflow periods are heavily impacted by significant increases in low-streamflow at Sanshui station and the increasing Sanshui/(Makou+Sanshui) streamflow ratio (e.g. Hou et al., 2004).

Increasing water levels were observed mainly along the coastal regions, which may be attributed to large amounts of sediment load from the upper PRD being deposited in the estuary (Zeng et al., 1992; Chen & Chen, 2002; Huang & Zhang, 2005) and increasing sea level (Zeng et al., 1992; Huang et al., 2000). The deposition process also occurred in the Yamen and the Shiziyang channels. The serious sediment deposition causes the river beds of these channels to rise and leads to a distinct backwater effect, which can be regarded as one of the main factors responsible for increasing high water level in these regions (Chen & Chen, 2002). Furthermore, the coastal regions are usually characterized by moderate- and low-intensity in-channel dredging, which further intensifies the increase in water levels in these regions (Fig. 1(b)). The spatial distribution of correlation coefficients between streamflow variations and water-level changes indicates weakening influences of hydrological processes but enhancing impacts of tidal levels of the Pearl Estuary on water-level variations from the upper to the lower Pearl River Delta.

**SUMMARY**

The Mann-Kendall trend test and kriging interpolation method from Surfer$^\text{TM}$ package were used to analyse the spatial and temporal patterns of the trends in extreme
high/low water levels in relation to different magnitudes of streamflow, exploring the impacts of different hydrological processes on the changes in water levels within the PRD region. Some interesting results were obtained, as follows:

- The streamflow at Makou station in January, April–June, and August–December is decreasing, but that in February, March and July is increasing. However, streamflow changes of Makou station are not significant at >95% confidence level. The streamflow at Sanshui station is increasing in all months and increases are significant except August. Streamflow in August is also increasing, but is not significant. The streamflow analysis results also indicate that the Makou/Sanshui streamflow ratio shows significant decreasing trend, implying that more streamflow was transferred to the North River delta. Further, a significant decreasing trend can be found in the low-flow periods (January–April; October–December) than in the high-flow periods (May–September). Streamflow ratio changes are among the important causes of changes in water levels across the PRD.

- The EHWLs in the high/normal flow periods are decreasing in the upper PRD and in the hinterland of the PRD region. The coastal regions and the Humen channel are characterized by increasing EHWLs. The EHWLs in low-streamflow periods exhibit different changing patterns in comparison with those in high-/normal-streamflow periods. Most parts of the PRD region are characterized by increasing EHWL in the low-flow periods. The ELWLs display similar changing patterns. The significant increasing Sanshui/Makou streamflow ratio in low-flow periods can be regarded as the main causes for increasing extreme high/low water levels in low-flow periods, especially for the increasing extreme high/low water levels in the hinterland of the PRD region. Based on the research by Huang et al. (1999, 2000), the increasing extreme high/low water level in low-flow periods can be considered as impacts of intensifying tidal activities in low-flow seasons. The general decreasing extreme high/low water levels in high-/normal-streamflow periods are mainly the result of in-channel dredging. The increasing water levels along the coastal regions are mainly due to increasing sediment load from upper stream and rising sea level and increasing siltation in the estuary regions.

- The correlation between extreme high/low water levels and streamflow changes indicate that the water levels in the upper PRD are mainly influenced by hydrological processes and those in the coastal regions are controlled by streamflow changes in the upper PRD and by tidal activity (e.g. Huang et al., 1999, 2000; Ou & Yang, 2004). The current study describes the changing characteristics of extreme high/low water levels and possible causes across the PRD, which will be of scientific and practical use in water resource management and mitigation of natural hazards under the changing environment in the PRD region. However, it should be noted here that the water levels of the PRD are controlled by more than one driving factor, e.g. in-channel dredging, tidal activity, levee construction, etc. The impacts of various driving factors on water-level changes across the PRD are dynamic and differ in different parts of the PRD. The current study discussed two important factors, i.e. streamflow changes and in-channel dredging. Further research is necessary for a better understanding and quantification of the water-level changes and their possible causes in the PRD region, one of the economically developed regions of China.

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