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The causes and impacts of water resources crises in the Pearl River Delta

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ABSTRACT

Owing to its combination of superior natural conditions and abundant resources, the Pearl River Delta (PRD), China, is densely populated, with concentrated industry and rapid development. The PRD is also one of the most threatened estuaries in the world, as it has been exposed to an increasing series of crises related to water resources. Water conflict, water pollution, and saltwater intrusion have all increased dramatically in the past few decades, which pose a threat to regional water security and impose constraints on regional development. The goal of this paper is to analyze the causes and impacts of some of the water resource crises faced by estuaries under dramatically changing environments, based on studies in the PRD. The PRD is centered around the Pearl River Estuary (PRE) and is the second most economically active district in China. Rapid economic development and a population boom have resulted in an average annual growth rate of 1.43% in water resource demand, which has further accelerated water pollution by a substantial growth in sewage discharge. Water pollution results in the impairment of the ecological functions of the water, and the standard rate of water function areas in the PRD remains under 50%. Large-scale and uneven sand excavations not only decreased the river discharge from upstream but also allowed more tidal prisms to enter, which triggered severe saltwater intrusion. Meanwhile, sea-level rise and changing wind patterns also contribute to increasingly severe saltwater intrusion, which was characterized by gradual increases in salinity, as well as more prolonged periods of higher salinity that exceeds acceptable thresholds occurring earlier in the year. This study is intended to bring attention to these challenging issues and provide some of the information needed to advance research into sustainability assessment of the water resources.

1. Introduction

As the most productive natural habitats in the world, estuaries provide important services that support economic activities and societies (Xu et al., 2016). Estuaries worldwide have been subject to rapid development and are among the most densely populated regions in the world. It is estimated that roughly 40% of the world's population, about 2.8 billion, currently live within 100 km of the coast, and there will be 4 billion people living along the world's coasts by 2100 (CIESIN, 2012). In recent years, intensive anthropogenic activities, including land reclamation for urban or industrial use, sand excavation, and dam construction (Sun et al., 2012; Chuai et al., 2014; Meyers et al., 2014; Anthony et al., 2015; Paiva et al., 2016; Andrews et al., 2017); and external natural phenomena, such as sea-level rise (Werner and Simmons, 2009; Hussain et al., 2014; Cui et al., 2015), have seriously affected the natural circulatory functions of many estuaries around the world (Frihy, 2003; Crossland et al., 2005; Kim et al., 2006; Jarvie et al., 2012; Statham, 2012; Abdrabo and Hassaan, 2015; Luan et al., 2016). The impairment of estuarine circulatory functions results in a high risk of water resource crises in estuaries, such as water pollution, flood hazards, loss of wetland habitats, eutrophication, and saltwater intrusion (Wang et al., 2013; Maskell et al., 2014; Watanabe et al., 2014; Gross and Hagy, 2017). These crises can cause immense loss of property and human life, and they have made estuaries more susceptible to environmental degradation (Branch, 1999; Elliott et al., 2014; Ribeiro et al., 2015). For instance, a great reduction in river discharge into the Yangtze River Estuary brought about a prolonged intrusion of saltwater into the estuary, which strongly influenced all of Shanghai's waterworks along the Huangpu River. A devastating algae bloom, which was the result of excess N and P nutrient concentrations, caused a water supply crisis

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that affected two million people in Wuxi City in 2007 (Chen et al., 2001; Li et al., 2009). Heavy metal pollution emergencies in the tributaries of the Pearl River, such as the North River's Cd pollution crisis in 2005, the Duliu River's As spill in 2007, the South Pan River's Cr contamination in 2011, and the Longjiang River's Cd emergency in 2012, have severely impacted upon the water supply and environmental health of these rivers.

Situated in the vicinity of the Pearl River Estuary (PRE), the Pearl River Delta (PRD) is surrounded by several cities: Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing, and is contiguous to Hong Kong and Macao. Its geographical advantages, reinforced by economic reform policies, have made the PRD a core economic region in Guangdong Province. With 4.27% of the total population (58.74 million people in 2015) and 0.57% of the land area (54,754 km^2) of China, the PRD has contributed disproportionately to China's economy, providing 9.12% of the national gross domestic product (GDP) in 2015 ($996.14 billion). Rapid social and economic development, as well as population growth, in the PRD has led to intensive anthropogenic disturbance to the water resource system, which has become increasingly prominent in recent years. On the one hand, the population boom and massive economic growth have contributed to continuously increasing water demand and the release of wastewater into rivers without effective purification treatment (Yang et al., 2017; Zhang et al., 2017). On the other hand, the rapid uneven degradation of the riverbed has triggered severe saltwater intrusions in the last two decades. As the source of sand and gravel for Hong Kong, large-scale excavation of river sand has occurred in the PRD since the mid-1980s, and the annual volume of dredged sand has been about 70 million m^3 for the last 15 years. However, the amount of sand supplied from upstream is not sufficient to replace the dredged sand (Zhang and Deng, 2010), and the degradation of the riverbed has led to changes in the hydrodynamics of the entire river network. Uncontrolled sand excavation has become one of the most significant anthropogenic effects on river discharge, water levels and divided flow ratio (DFR) between various watercourses of the PRD since the 1980s, which has ultimately aggravated the intrusion of saltwater (Lv and Du, 2006; Luo et al., 2007; Zhang et al., 2009). The effects of sea-level rise and wind on saltwater intrusion were also found in the PRD. The severity of saltwater intrusion is largely related to the expected rate of sea-level rise, which severely affected the freshwater resources. The winter prevailing wind can distinctly enhance the intrusion of saltwater into the PRE (Huang et al., 2004; Zhou et al., 2012a; Wang et al., 2012).

A large number of studies have investigated estuarine water resource crises, as well as relevant issues such as hydrology, sedimentation, saltwater intrusion, water quantity and quality, and ecosystems (Table 1). The goal of this paper is to present a comprehensive explanation for the causes and impacts of water resource crises in the PRD. The findings will provide important information and function as reference material for the management of water resources in the PRD, and for research into typical estuaries around the globe.

2. Study area and data

The PRD is located in the downstream alluvial plain of the Pearl River from 21°30′ N to 23°42′ N, and from 112°26′ E to 114°24′ E (Fig. 1), covering an area of about 3000 km^2. As the second largest river in China (Zhao et al., 2014), the Pearl River has three major tributaries: the West River, the East River, and the North River. The runoff discharges into the South China Sea through eight outlets, which are, in sequence from east to west, the Humen, Jiaomen, Hongqimen, Hengmen, Modaomen, Jitimen, Hutiaomen, and Yamen Waterways. The PRD lies in a subtropical region with features of a subtropical monsoon climate. Annual precipitation ranges from 1200 to 2200 mm, and precipitation from April–September accounts for 82%–85% of the yearly total. Owing to its high precipitation, the PRD is considered to have one of the world's most complicated fluvial networks. The dense river network provides favorable conditions for the development of irrigation agriculture and transportation, laying a solid foundation for economic growth and social development.

The development and the growth rate of the economy and society of the PRD were analyzed and compared to those of several developed regions in the world. The socioeconomic data used in this paper were taken from the Guangdong Statistical Yearbook, the Tokyo Statistical Yearbook, the World Bank Database, the Food and Agriculture Organization of the United Nations Database, and the Bureau of Economic Analysis of the United States. These data included measurements of GDP, industrial structure, and population from 1980 to 2015.

Data about the utilization of water resources included water resources demand, water use index, and water quality. The hydrological, terrain and meteorological data used in this paper included salinity, saltwater intrusion extent, river discharge, tidal elevation, river channel bathometry, and wind direction. These data were all obtained from the Hydrological Bureau of Guangdong Province and the Hydrological Yearbook. The reliability and homogeneity of the data series were strictly checked before they were released. The salinity series and saltwater intrusion extent series were observed at 17 stations along the Modaomen Waterway (MW) from October 2000 to March 2012. Daily upstream river discharge was measured at the Sanshui and Makou stations from 1965 to 2012. Daily tidal data from 1965 to 2012, as recorded at the Sanzao

Table 1
Summary of previous studies about relevant issues of water resource crises.

Topic	Findings	References
Water pollution	Water pollution changes the environment conditions	Fang et al. (2003); Zhang et al. (2017); Yang et al. (2017)
Changes in channel geometry	River channels were significantly undercut by large-scale sand excavation	Luo et al. (2007); Wu et al. (2014); Zhang et al. (2010)
	Degradation of the riverbed lead to changes in hydrodynamics	Lv and Du (2006); Luo et al. (2007); Zhang et al. (2009); Zhang et al. (2010); Zhang and Deng (2010)
Saltwater intrusion	Decrease of river discharge from upstream can aggravate saltwater intrusion	Lv and Du (2006); Becker et al. (2010); Yuan et al. (2016)
	Sea-level rise is responsible for saltwater intrusion	Huang et al. (2004); Werner and Simmons (2009); Gong and Shen (2011); Zhou et al. (2012a); Hussain et al. (2014); Hussain and Javadi (2016);
	Previaling wind can enhance saltwater intrusion	Wong et al. (2003); Gan et al. (2004); Ji (2008); Wang et al. (2012); Zhou et al. (2012b); Zheng et al. (2014)
	Effects of saltwater intrusion on ecosystem	Long et al. (2013); Xie et al. (2014); Liu et al. (2014); Pettit et al. (2016); Yin and Harrison (2008)