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Analysing monthly sectorial water use and its influence on salt intrusion induced water shortage in urbanized deltas

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ABSTRACT

Urbanizing delta regions face seasonal water shortages induced by rising salt intrusion. Decreasing river discharge is readily listed as the major cause of water shortage events. Yet, observations of river discharge often fail to support this attribution. Evidence of the association between severe salt intrusion and water use is weak and inconclusive. The present study asks to what extent water use contributes to salt intrusion and freshwater shortages. Moreover, it asks whether management of water use rather than water supply can be part of mitigating salt intrusion. The contribution of water use in causing severe salt intrusion events is assessed by first quantifying monthly sectorial water use and next comparing it with threshold discharges from the graded salt intrusion warning system. The case study region is the Pearl River Delta, China. Sectorial water use is found to substantially vary between months. In particular in the dry month in which water shortages are reported, water use can be more than 25% of discharge and thus exacerbates salt intrusion. Evaluation of coping strategies shows that improved water use can alleviate salt intrusion by up to one level in the warning system, thus preventing problems at a number of water abstraction points.

1. Introduction

Water shortage is one of the major challenges of this century (Falkenmark et al., 1997; Postel, Daily, & Ehrlich, 1996; Vörösmarty, Green, Salisbury, & Lammers, 2000). Monsoon delta regions, in particular, suffer seasonal water shortages during the dry season as these regions are characterized by a pronounced uneven distribution of rainfall and runoff (Caballero, Rimmer, Easton, & Steenhuis, 2012; Cornforth, 2012; Islam, Chou, Kabir, & Liaw, 2010; Merz et al., 2003). These problems will likely be exacerbated with further global warming (Vörösmarty et al., 2000). Water shortage is also a quality issue. Water quality can be degraded by pollution from sewage, agricultural residues, and industrial waste. In delta area salt intrusion can also degrade water quality below acceptable levels and causes shortage events (Werner et al., 2013). Water shortages in China's Pearl River Delta (PRD) have been reported as a result of increasingly severe salt intrusions during the dry season (Liu, Chen, & Lou, 2010).

Before 2000, about twice per decade the salt intrusion could not be supressed by the Pearl River discharge, threatening the freshwater supply in the PRD (Kong, 2011). After 2000, the frequency of the severe salt intrusion has sharply increased. Since then, coastal cities in the PRD have suffered almost every year from salt intrusion induced water shortages, and eventually resulted the implementation of the inter-regional water transfer in the PRB to provide extra fresh water supply to the PRD (Chen, Chen, Lai, & Zeng, 2006; He, 2007; Huang, 2009; Sun, 2008).

The severe salt intrusions have instigated investigations in background, causes and impacts. The majority of studies report low discharge as the main cause of severe salt intrusion events. Zhu, Shen, Lin, and Suo (2007) found salinity increased considerably with the decreasing discharge. Kong (2011) then confirmed the main factor responsible for the severe salt intrusion in 2009–2010 was reduced runoff in the Pearl River. Later research has also revealed relationships between discharge at an upstream hydrostation and chloride concentration at the estuary channel (Hu & Mao, 2012).

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Although the observed increasing frequency and intensity of successive droughts in 2000s has exceeded the driest period of the last century, the total annual rainfall of the Pearl River Basin (PRB) is reported stable (Ji et al., 2009). Recent studies also show that hydrological conditions in the PRB have remained stable since 1950s. Both precipitation in the PRB and discharge of the Pearl River are found to either show no significant trend (Zhang et al., 2008; Zhang, Yan et al., 2009), or even to show significant increases in dry season (Chen, Zhang, Chen, & Wang, 2012; Zhang, Xu et al., 2009).

Other factors, which could enhance salt intrusion have also been studied, such as sand excavation (Han, Tian, & Liu, 2010; Luo, Ji, & Yang, 2006), sea level rise (He, Lu, Tu, & Chen, 2012), and wind direction (Li, Zhang, & Wang, 2009). Only Chen (2006) discussed water use and management aspects.

Chen (2006) concludes that the water management system in the PRD neglects managing the water uses because the PRD is a water abundant region. In previous work we confirm that on annual time scales the PRD has enough water supplies to fulfil its water use[1] (Yao, Werners, Hutjes, Kabat, & Huang, 2015). Nevertheless, seasonal water shortages have occurred due to the severe salt intrusion. This indicates a need to understand the influence of water use on salt intrusion on a monthly basis in the PRD. Thus the present paper addresses the following questions:

Can water use contribute to the salt intrusion induced water shortage?

Can management of sectorial water use help alleviate salt intrusion and water shortages?

To answer these questions five coastal cities were selected within the PRD in a case study (Section 2.1). The reported shortage events and their causes were reviewed for the period 2000–2010. Water use and discharge data were gathered for the same period (Section 2.2). A conceptualization of off-stream water use previously developed for the PRD was then elaborated to allow the monthly sectorial water use analysis (Section 2.3). Influence of monthly sectorial water uses on salt intrusion thus can be assessed (Section 2.4), while the current and potential improvement strategies can also be tested (Section 2.5). Next, results are presented (Section 3). Then, practical implications of findings are discussed (Section 4.1), followed by a discussion of the uncertainties (Section 4.2) and study outlook (Section 4.3). Finally, conclusions are drawn (Section 5).

2. Materials and method

2.1. Study area

The Pearl River Delta (PRD) is located in Guangdong province, southeast China (Fig. 1). West River and North River, the largest two tributaries of Pearl River, converges near the border of Foshan, and then soon bifurcates, entering a complex distributary system before drains into the estuary through eight river outlets. Almost all the runoff flowing into the PRD comes from these two tributaries (Water Resources Department of Guangdong Province, 2000-2011). Two hydrologic stations measure the discharge of the two rivers at Makou and Sanshui. The joint discharge measured at these two stations is often referred to as the Sixianjiao Discharge (Q_{SD}), which typically varies from less than 2000 $m^3 s^{-1}$ in the dry season (winter-spring) to 32,000 $m^3 s^{-1}$ in the wet season (summer-autumn). Five PRD cities were selected as the study area covering the above described sub-system: Guangzhou, Foshan, Zhongshan, Zhuhai, and Jiangmen. This area covers about half of the total area and population of the PRD. More than 80% of water supply to the off-stream water use of the study area comes directly from the Pearl River channels. Only Jiangmen supplies 50% from local reservoirs. The other four cities have limited storage capacities to capture and utilize the local precipitation. Local reservoirs contributes 11% of Guangzhou's water supply, whereas only 3.5% for Zhongshan.

Salt intrusion has been reported to occur in the PRD between October to March when discharge from upstream is low and the sea water is able to progress further upstream, especially during high tides, through all the eight outlets to the South China Sea (Wang, Zhu, Wu, Yu, & Song, 2012). This affects the water quality in the higher upstream regions of the delta where the freshwater inlets are. Since almost all the off-stream water use is supplied by surface water, the intrusions become problematic when salinity causes chloride to exceed 250 $mg L^{-1}$, the upper limit of freshwater standards in the PRD (Luo et al., 2006). Before the dry season 2004–2005, the Pearl River Water Resource Commission (PRWRC) conducted an assessment to estimate salt intrusion and its possible impact on water supply. The assessment found that Q_{SD} significantly correlated with the daily average salinity-over-standard period in the main PRD distributary channels (Wen, Chen, Liu, & Yang, 2007). As a result, a graded salt intrusion warning system was established (Wen & Yang, 2006). The warning system defines five alerting Q_{SD} levels (Q_{ASD}), each corresponding with a different impact of salt intrusion. We adopted these Q_{ASD} levels as indicators to assess the possible impact of salt intrusion under given hydrological conditions. Table 1 and Fig. 2 show how the inland fresh water inlets may be affected by salt intrusion when Q_{SD} decreases.

2.2. Data

Two sets of literature were reviewed to gain more insights into the shortage reported in the PRD during 2000–2010. The first set consists of peer-reviewed articles that explore the causes of the events. The second set is governmental reports and statistics from which data to assess water uses and discharge were collected.

The "Guangdong Water Resource Bulletin", an annual government report, is the main source for sectorial water use and water use intensity of each city (Water Resources Department of Guangdong Province, 2000-2011). To obtain consistent trends of sectorial water uses during the study period, data homogenization as reported by Yao et al. (2015) was also applied here.

Monthly drinking water withdrawal has been reported since 2003 by the Department of Environmental Protection of Guangdong Province[2] (GDEP). The reported data include monthly withdrawals from the major water inlets in the PRD. The aggregated annual freshwater withdrawal of the PRD reported by GDEP was found comparable to the region's domestic water uses as reported by the Water Resource Bulletin. Here monthly drinking water withdrawal was used to represent monthly domestic water use.

Monthly Q_{SD} data were collected from 2001 to 2011, with the exception of 2006 for which was not available (Hydrology Bureau of Ministry of Water Resources, 2001-2005, 2007-2011). Meteorological data reported by the National Meterological Information Center[3] and socio-economic data from the regional statistic yearbooks (Guangdong Statistics Bureau, 2000-2013) were collected as drivers to compute the sectorial water uses. No meteorological data was available for Zhuhai specifically. Data from Macau[4] were used as the two cities are in the same area.

[1] The term "water use" in the present paper refers to water withdrawal. Note that the "water use" does not refer to "water consumption" defined as water withdrawal minus return to the river system after usage (e.g. irrigation, manufacturing).

[2] Source: www.gdep.gov.cn.

[3] Source: cdc.cma.gov.cn.

[4] Source: www.smg.gov.mo.