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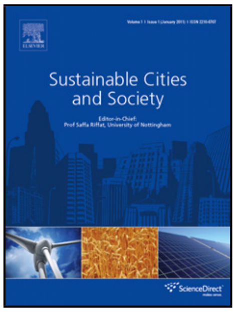

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Author: Mingtian Yao Dan Yan Pavel Kabat Heqing Huang Ronald W.A. Hutjes Saskia E. Werners

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

Mingtian Yao[a]*, Dan Yan[a,c], Pavel Kabat[b], Heqing Huang[c], Ronald W.A. Hutjes[a], Saskia E. Werners[a]

[a] *Water System & Global Change, Wageningen University and Research Centre, PO Box 47, 6700 AA Wageningen, The Netherlands ;*

[b] *International Institute for Applied Systems Analysis, Laxenburg, Austria;*

[c] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, UCAS, 11A Datun Road, Chaoyang District, Beijing, 100101, China*

* Corresponding author. E-mail: mingtian.yao@wur.nl

Highlights

- Off-stream water use decreases discharge and thus exacerbates salt intrusion.
- Water shortage in a complex delta results from interplay of the dynamic processes.
- Hydro-engineering strategy alone cannot solve salt intrusion problem in the PRD.
- Improved water management policy can help alleviate the threats of salt intrusion.

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.

Keywords: water use; salt intrusion; water shortage; water use efficiency; urbanized delta; Pearl River Delta

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 (D. D. 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 (X. Chen, Chen, Lai, & Zeng, 2006; Z. 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 (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 hydro-station and chloride concentration at the estuary channel (Hu & Mao, 2012).

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 (S. Zhang et al., 2008; W. Zhang et al., 2009), or even to show significant increases in dry season (Y. D. Chen, Zhang, Chen, & Wang, 2012; Q. Zhang 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 (Y. 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).

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[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. Materials and Method

2.1. Study area

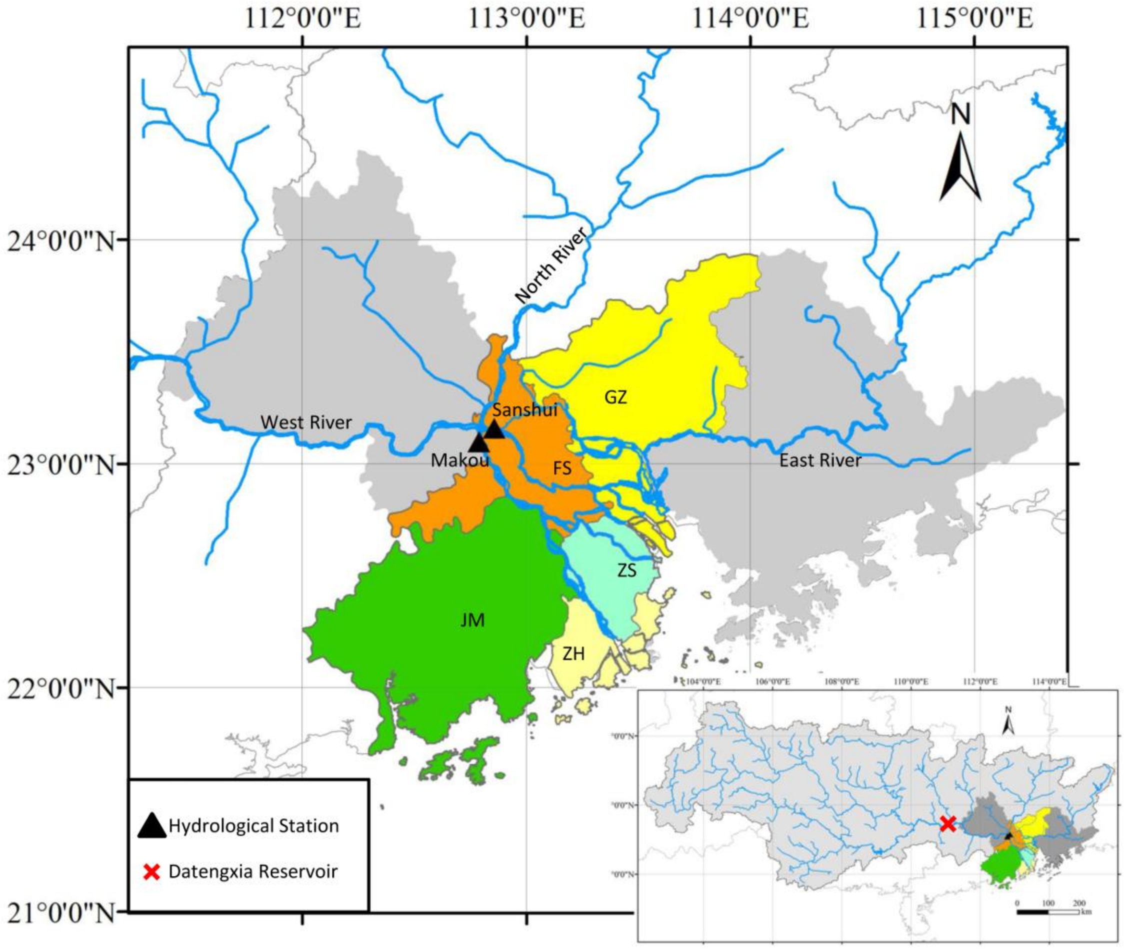

Figure 1. Study area of the Pearl River Delta. Shown are the 5 municipalities Guangzhou (GZ), Foshan (FS), Zhongshan (ZS), Zhuhai (ZH), and Jiangmen (JM) of the PRD (include the dark grey areas) and the two discharge stations, Makou and Sanshui that measure the total inflow to the delta from the West River and the North River, the Sixianjiao discharge (QSD). The inset shows the entire Pearl River Basin with the location of the Datengxia reservoir.

The Pearl River Delta (PRD) is located in Guangdong province, southeast China (Figure 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^3s^{-1} in the dry season (winter-spring) to 32,000 m^3s^{-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 mgL^{-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 Figure 2 show how the inland fresh water inlets may be affected by salt intrusion when Q_{SD} decreases.

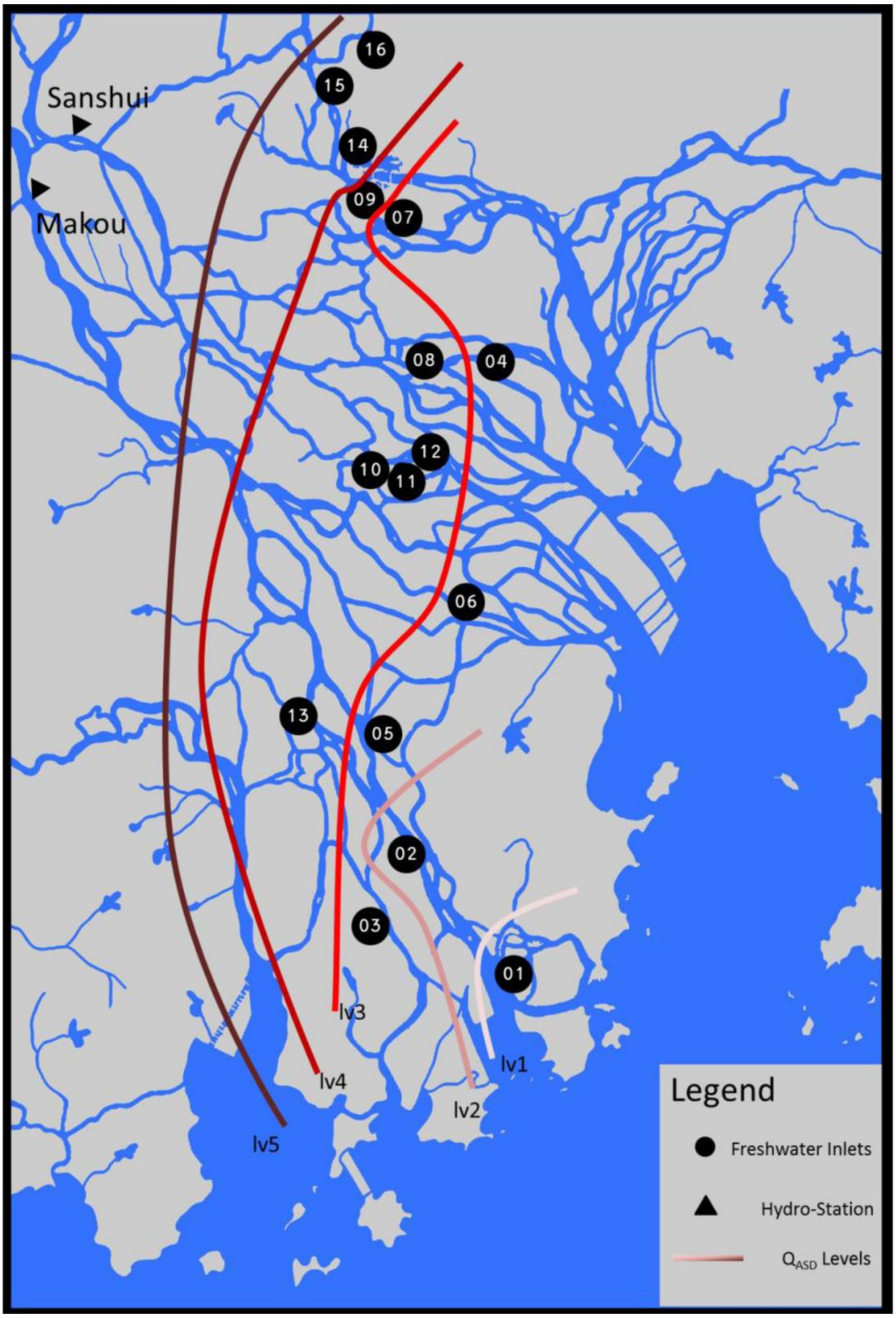

Figure 2. Possible impact of salt intrusion associated with Q_{ASD} levels. The pink to purple lines indicate the limit of salt intrusion associated with progressive Q_{ASD} levels. The numbered dots are major water abstraction points. Note the lines in the graph indicate the salt intrusion warning levels only, rather than the actual salinity contour line.

Table 1. Salt Intrusion Warning System based on Q_{ASD} level

Q_{ASD} level	Q_{SD}	Threats	Inlets Affected	Inlets Under Threats
1	4500 m^3/s	Reservoirs in Zhuhai should start retaining	-	1
2	3500 m^3/s	Water supply of Zhuhai will be compromised	1	2
3	2500 m^3/s	Guangzhou will be affected	1-4	5-7
4	2000 m^3/s	Zhuhai, Zhongshan, Guangzhou will be largely affected. Jiangmen maybe affected	1-8	9-13
5	1500 m^3/s	Water supply of Zhuhai, Zhongshan, Guangzhou may be stopped temporally	1-9	9-16

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.

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

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

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

2.3. Monthly water use

We assessed water use in three sectors: domestic, manufacturing, and irrigation. A simple conceptualization of off-stream water use and its driving forces was previously developed for the PRD (Yao et al., 2015). The conceptualization uses relations typical in global sectorial water use assessments, which correlate water use to socio-economic driving forces. It allowed for evaluating annual water use in PRD based on better reported socio-economic data for the region. This study elaborated the conceptualization to monthly basis.

2.3.1. Monthly domestic water use

It is unknown where exactly the GDEP reported withdrawal is supplied to. Thus the monthly domestic water use was calculated by first constructing an average monthly distribution from the available data on drinking water withdrawal. Next, annual domestic water use is multiplied by this distribution to yield the monthly values. It is assumed that that the reported drinking water withdrawals are for domestic purposes only.

2.3.2. Monthly manufacturing water use

Manufacturing water use (W_{MAN}) is expressed as a product of manufacturing water use intensity (I_{MAN}) and corresponding manufactural Value-Added (VA_{MAN}):

$$W_{MAN} = I_{MAN} * VA_{MAN} \quad (1)$$

Although I_{MAN} changes over time, changes are gradual (Yao et al., 2015). Its value can be assumed constant over one year. Thus the monthly fluctuation of manufacturing water use is represented by the fluctuation of the VA_{MAN}. Monthly VA_{MAN} statistics are collected to compute each city's monthly W_{MAN}.

2.3.3. Monthly irrigation water use

Irrigation water use was calculated for each city following the same method as of the previous study for the PRD (Yao et al., 2015). More local specified meteorological data were gathered to improve the accuracy (see Section 2.2).

2.4. Coping strategies

Two coping strategies to alleviate the impact of severe salt intrusion were defined. One strategy is the current common measure that receives extra water supply from upstream basin (ES strategy). The other one is improved water management policy (MP strategy).

The strategy to receive “extra supply” (ES) refers to the current government strategy that addresses severe salt intrusion with engineering projects(D. Liu, Chen, & Lou, 2009) . The strategy comprises the release of large amounts of freshwater from the upstream basin to the PRD when severe salt intrusion is projected to occur (Huang, 2009). The Datengxia Reservoir currently under construction on the upstream West River is the latest effort in this strategy. The reservoir is located nearby the PRD on the upstream West River, and is expected to be able to increase the Q_{SD} by 520-580 m^3s^{-1} (Shen & Zhu, 2010), thus help resolve the salt intrusion problem for the future (S. Zhang et al., 2008). The present study examined the minimum (520 m^3s^{-1}) and the maximum (580 m^3s^{-1}) anticipated improvement to assess how much the Datengxia Reservoir may help relieve severe low-flow conditions.

To explore the possible contribution of water use management in combating salt intrusion, the MP strategy was developed. The MP strategy assumes a sectoral water use reduction by adopting the current globally advanced sectorial water use efficiencies in the PRD, regardless of the present economic development and water use behaviours. By reducing water use, more water resource will remain in the river channels, thus increase the river discharge and improve the salt supressing capacity.

For the MP strategy the manufacturing water use efficiency (53 m^3 per 10,000Yuan VA_{MAN} in 2010) was reduced to the level of Germany[5] in 2010 (12 m^3 per 10,000 Yuan VA_{MAN}). Germany was selected as its manufacturing sector is similar to the PRD. Both are dominated by electronics, chemicals, and transportation machinery. This similarity implies that in principal, the PRD could be able to improve the manufacturing water use efficiency to the German level.

Irrigation water used is affected by various factors such as irrigation system, crops and climate. Irrigation efficiency varies from 0.4-0.95 depending on the applied irrigation system (Howell, 2003). The present study adopted 0.78 for the MP scenario from a present value of 0.6 in the PRD. The 0.78 is realized in Bangladesh[4], which is among the best operated irrigation systems in the world. Both the cultivation sectors in Bangladesh and in the PRD are dominated by rice.

The domestic water use efficiency in the MP scenario was set to 115 litres per person-day, the average value of the EU[4] in 2010, compare to an average 264 litres per person-day for the PRD in 2010.

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[5] Source: EUROSTAT

3. Results

3.1. Monthly discharge

The average Q_{SD} during the dry season was 3700 m^3s^{-1} from 2001 to 2010. The lowest monthly low-flows during the study period all appeared in 2004. The average monthly Q_{SD} in 2004 was less than 2200 m^3s^{-1}, with 2094 m^3s^{-1}, 2130 m^3s^{-1}, 2195 m^3s^{-1}, 2537 m^3s^{-1}, 2180 m^3s^{-1}, and 1987 m^3s^{-1} in January, February, March, October, November and December respectively.

3.2. Monthly sectorial water use

On average, the study area used the most water in October and the least water in February, with an overall average monthly water use of 1224 million m^3 during the study period. The average water use in October is 1844 million m^3, accounting for 12.6% of the annual total, and is 50% more than the overall monthly average. The average water use in February is 921 million m^3, accounting for 6.3% of the annual total, and is 25% lower than the overall monthly average.

Irrigation contributed the most to the monthly variation in comparison with the manufacturing and domestic sectors. On average, irrigation was estimated to use 946 million m^3 water in October, while using only 75 million m^3 in June. Irrigation is also the only sector using more water in the dry season than in the wet season. Irrigation water use in the dry season is about 60% more than in the wet season. The late-rice in particular uses up to 28% of water during the dry season. Manufacturing is the dominant water user in the study area, using 615 million m^3 per month on average during the study period. The monthly manufacturing water use shows an increase trend through the year, with the minimum and maximum uses in February and December at 449 and 741 million m^3, respectively. Domestic sector used the least water of 229 million m^3 per month on average, with the maximum of 255 million m^3 in August and minimum of 182 million m^3 in February.

3.3. Off-stream water uses versus discharge

The disagreement between the reported main reason for severe salt intrusion and stable hydrological condition suggests that discharge alone, as water supplied from the upstream basin to the PRD, cannot fully explain the salt intrusion induced water shortage in the 2000s.

On average, 11-15% of the Q_{SD} was withdrawn for off-stream uses in the dry season during the study period. In the driest year of 2004, up to 28% of the Q_{SD} was withdrawn. As shown in Figure 3, off-stream uses could have affected the salt-suppressing ability of Q_{SD} substantially especially in the dry years. Less freshwater was kept in the channel to suppress the salt intrusion. Compared to the Q_{ASD} level, the impact of salt intrusion was exacerbated by off-stream water use from level 4 to level 5 in December, and from level 3 to level 4 during the remaining dry months under the low flow conditions as in 2004. This means eight more freshwater inlets would be affected by salt intrusion throughout the dry season, while another three would be affected in December.

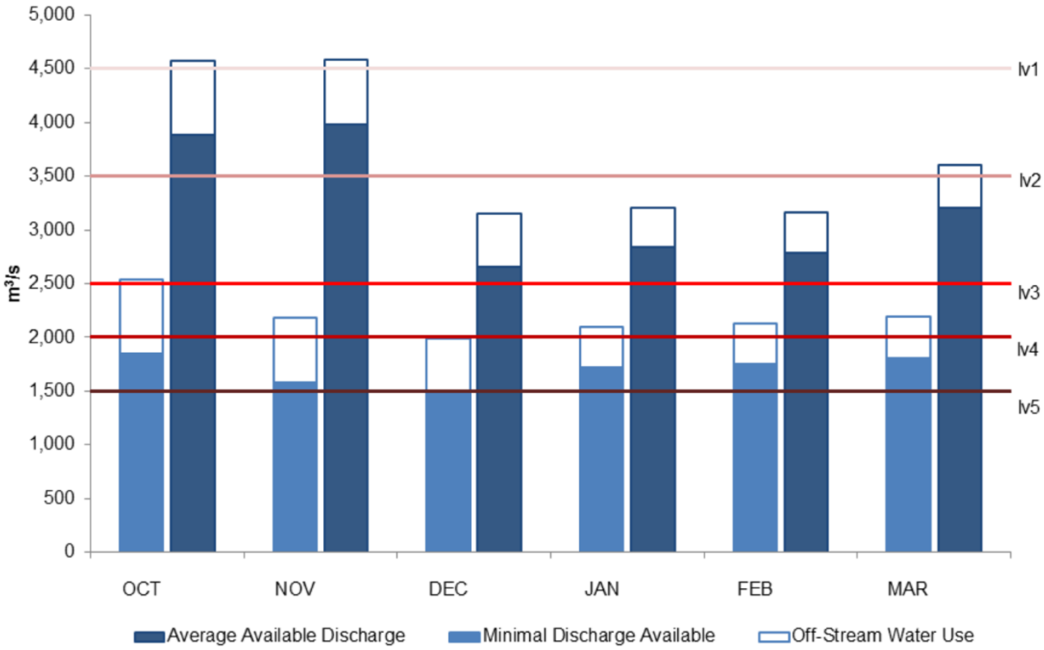

Figure 3. Comparing average off-stream water use with average monthly QSD (dark blue) and minimal monthly QSD (light blue) during the study period. The overall height of the bar represents the QSD volume. Blank frames represent the water withdrawn for off-stream uses.

Turning back to 2004 when the severe salt intrusion was reported in winter, the results found remarkable low-flow of the Q_{SD}, and high level of the water use. The Q_{SD} in November and December 2004, and January 2005 was all below the Q_{ASD} level 3. Contrarily, the water use in these three months was among the highest monthly water uses during the study period. A most striking aspect of the data is the magnitude of the freshwater released from far upstream reservoirs to ensure the delta water supply during the severe salt intrusion in comparison with the water use. Water use surpassed the 760 million m^3 freshwater released in January 2005 by almost a factor of two.

3.4. Potentials of the coping strategies

The potential impact of the Datengxia Reservoir and the MP strategy on reducing salt intrusion were evaluated. As shown in Figure 4, the strengthened Q_{SD} by the Datengxia Reservoir would relieve the impact of salt intrusion during dry years as in 2004. The increased minimum 520 m^3s^{-1} discharge would enhance Q_{SD} by one Q_{ASD} level throughout the dry season. As a result, freshwater inlets number 8-16 would be released from the impact of salt intrusion except in the driest December, whereas risk on inlets number 5-7 would become lower. Yet still, the impact of salt intrusion could be severe, especially in December. The freshwater inlets of Guangzhou would still likely be compromised throughout the dry season. Most part of the study area would still be affected under the condition of December 2004. The maximum anticipated 580 m^3s^{-1} extra discharge will slightly reduce the risks, but will not change the overall picture.

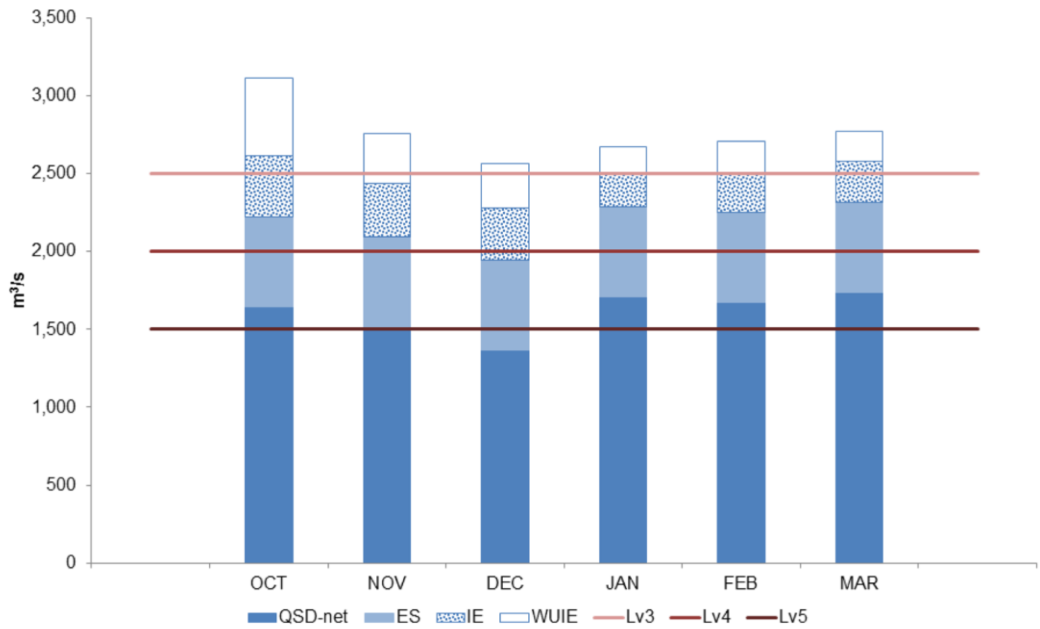

Figure 4. Effect of the ES and MP strategy on saving Q_{SD} for suppressing the salt intrusion in 2004-condition. The overall height of the bar represents the Q_{SD} volume. QSD-net is the "net" Q_{SD} after extraction for off-stream uses; ES is the expected minimum improvement of the Datengxia Reservoir; MP is the lump-sum improvement of the MP strategy; WUMP is the improved total off-stream water use after implementing the MP strategy. The observed Q_{SD} in 2004 is the sum of $Q_{SD\text{-}net}$, MP, and WUMP

In addition to the contribution of the Datengxia Reservoir, Figure 4 also illustrates the further improvement of the MP strategy on the Q_{SD} and the resulting influence on salt intrusion during the low-flow conditions as in 2004. The improved water use efficiency resulted in a reduction of off-stream water use of 53% in 2004. In total, more than 4700 million m^3 water saved during the dry season by implementing the improved water use efficiency in different sectors, which is equivalent to 300 m^3s^{-1} on average, i.e. about half of the Datengxia Reservoir's influence. Consequently, under the 2004 condition, Q_{SD} would be increased from Q_{ASD} level 3 to level 2 in January, February, March and October, and from level 4 to level 3 in December. Freshwater inlets number 8-16 would be released from threats of salt intrusion throughout the dry season. Risk of severe salt intrusion on the remaining freshwater inlets would also be relieved in November and December.

4. Discussion

The present study aims to assess the contribution of off-stream water use in both causing and relieving the severe salt intrusion in the urbanized delta regions. Our results corroborate the idea of Augustijn et al. (2011), who suggested that proper management of the off-stream water use was able to generate the required discharge to alleviate the salt intrusion problems in the delta region.

Moreover, our findings indicate that an impact easily assigned to climate change is at least partially caused by human activities. As for the salt intrusion that can be easily attributed to the result of climate change induced discharge decline and sea level rise, human activities such as off-stream water uses is also part of the story (Q. A. Zhang, Xu, & Chen, 2010).

4.1. Uncertainty

Uncertainties rise from implementation of the coping strategies, the calculation of monthly water use, and future development of the upstream basin.

4.1.1. Uncertainty in current strategy

We show that the anticipated extra supply from Datengxia reservoir can release part of the delta area from the impact of salt intrusion. However, this result is subject to the assumption that the Datengxia reservoir will increase the QSD as expected. Whether the reservoir can provide the expected extra supply is strongly affected by future hydrological conditions, i.e. if the total water resources in the PRB decrease due to the climate change, building new reservoirs may not achieve the expected contribution in alleviating the salt intrusion problem. Previous study shows that low flow of the Pearl River could decrease by more than a half due to the climate change (Yan, Werners, Ludwig, & Huang, 2015). Thus, if the Datengxia-increased Q_{SD} drops from the maximum anticipated value by 20% to 460 m^3s^{-1}, freshwater inlets number 8-16 may be affected again in November (Figure 2). If the Datengxia reservoir can only supply half of the anticipated improvement, the above mentioned freshwater inlets may be affected all through the dry season.

Moreover, the current salt intrusion warning system (Q_{ASD}) that is based on historical observations may also be affected by climate change, e.g. sea level rising. Previous research shows that the severe salt intrusion significantly moves up stream due to the sea level rise (Y. He et al., 2012; Kong, Chen, Du, & Chen, 2010). This indicates that a larger Q_{SD} will be required to combat severe salt intrusion under future conditions.

4.1.2. Uncertainty in sectorial water use

The MP strategy only improved irrigation efficiency, which depends on many factors that all remain uncertain whether the future conditions will change in favour of off-stream water use reduction. For instance, replacing second rice by establishing greenhouses may reduce agricultural water use. But the current "prime cropland preservation" regulation is hold to ensure food security by allowing certain amount of cropland only for production of grains, cotton, oil crops and open-field vegetables. Whether or not the policy will be adjusted remains uncertain.

Next, influence of the improved domestic water use efficiency may be overestimated. Prior studies suggest domestic water use in the developed country is significantly influenced by outdoor applications like home gardening (Domene & Sauri, 2006; Syme, Shao, Po, & Campbell, 2004). These applications are currently rare in the PRD due to the less developed economy, but are generally pursued as a symbol of high social status. What lifestyle would the PRD inhabitants choose to have in future remains uncertain.

We selected the German manufacturing water use intensity in 2010 as the possible target for the PRD. Apart from the discussed similarities, Germany manufacturing sector has smaller scale of the textiles and leather industry than the PRD, both of which require large amounts of water for production. The PRD may still need structural optimization to achieve the water use efficiency of Germany. Otherwise the effectiveness of the MP strategy may be altered by the different water use intensity achieved in the PRD.

4.1.3. Uncertainty from upstream basin

Off-stream water use in the upstream basin may lead to greater uncertainty in achieving the expected salt suppressing capacity improvement in the PRD. Firstly, the upstream basin has larger scale of population and economy than the PRD, which needs more water for off-stream uses. In 2010, for example, the upstream West River Basin used 35 billion m^3 water (PRWRC, 2011), more than twice the 15 billion m^3 of the PRD. Secondly, the present findings suggest that irrigation contributes the most to the monthly water use fluctuation. The upstream basin is far less industrialized than the PRD. Irrigation water use accounted for 64% in the upstream West River Basin, twice as much as of the study area in 2010. This doubled relative irrigation water use should make the monthly water use even more imbalanced, and should have a greater influence on salt intrusion. By applying the MP strategy to the upstream irrigation system, some 5 billion m^3 extra water would be made available to strengthen the Q_{SD} by a further 300 m^3s^{-1} throughout the dry season. Thus, most of PRD would be protected from severe salt intrusion even under the circumstances as in 2004.

4.2. Policy Implications

Although the Datengxia hydro-engineering project is often considered as *the* necessity to alleviate severe salt intrusion problems (D. Liu et al., 2009), our result indicates that improved water management policy (MP strategy) is an additional option for policy makers to take up the challenge. First, as the latest key hydro-engineering project in the PRB, the Datengxia reservoir is expected to alleviate the salt intrusion damage by providing extra discharge for salt suppression in the estuary. Our results show that improved water management policy (MP strategy) can provide similar benefits by increasing water use efficiency. Secondly, our result also indicates that the impact of salt intrusion could still be severe especially during the dry year regardless of the operations of the Datengxia reservoir. The Pearl River discharge is likely to reduce throughout the basin during the dry season due to climate change (Yan et al., 2015). This may result in a further insufficient salt suppressing capacity of the Datengxia reservoir alone in future.

In addition, building more reservoirs/dams may not be an easy option for the PRB. Pearl River discharge at downstream area can hardly be affected by reservoirs/dams at upstream basin (S. Zhang et al., 2008). Constructing large reservoirs/dams in the downstream area is strongly restricted by the fast growing population, and shrinking land resources (L. Zhang, 2002). Contrary to the engineering projects, improving water management to reduce water use can further increase the salt suppressing capacity in addition to the contribution of the current infrastructures. In addition, future development of the upstream PRB may increase the upstream water use and further reduce the downstream discharge (see section 4.2.3 for more discussion). Thus, confronting future severe salt intrusion challenges under changing climate and socioeconomic conditions will most likely require combining both strategies.

Moreover, in the study area, Guangzhou (GZ) and Foshan (FS) are inhabited by about 70% of the total population. Consequently, together they account for about 70% of domestic water use and 80% of industrial water use of the whole area. Moreover, Guangzhou alone takes up 1/3 of the total irrigation water use. These two cities are also located more upstream than other cities (Figure 1). This indicates that emphasizing the MP strategy in these cities is more important and more efficient to achieve the expected improvement in salt suppressing capacity.

4.3. Study outlook

The present study shows that off-stream water use can affect salt intrusion by decreasing discharge. For a complex delta region like the PRD a conclusive assessment of this effect requires detailed study, including sub-channel discharges and spatial distribution of water users. Future studies with such data available could result in more complete understanding of solutions to the salt intrusion induced water shortage through water use management.

Another crucial question to be asked is, what will the future look like? Combined effort of the ES and MP strategy could effectively address most the severe salt intrusion in the PRD. But the factors discussed above can be negatively affected by many dynamic processes such as climate change and further economic development, especially in the upstream basin due to its greater scale in population, economic activities, and further development capacities. A further study with a focus on future land use and water scenarios in both the delta and the entire basin is recommended.

5. Conclusion

The present study finds that off-stream water use contributes to the occurrence of the severe salt intrusion, resulting seasonal water shortage in China’s Pearl River Delta. Sectorial water uses exhibit significant monthly dynamics in the PRD. The total off-stream water use in the dry season is 12% more than in the wet season. Irrigation, in particular, uses 58% more water in the dry season than in the wet season. Withdrawals in the dry season is more than 25% of discharge, deteriorated the salt-suppressing capacity of the runoff, thus contribute to the salt intrusion.

The present study further evaluated two coping strategies, extra releases from upstream (ES), and improved water management policy (MP). The results indicate that the ES strategy alone cannot resolve the severe salt intrusion in the PRD, especially during dry years like 2004. Additional to the current strategy, MP can protect most parts of the study area from the threats of severe salt intrusion. Off-stream water use management in the upstream basin may be even more important than inside the PRD, to maintain the Sixianjiao discharge (Q_{SD}), which is crucial for the delta to combat severe salt intrusion. This study shows how freshwater shortages in a complex delta system result from the interplay of dynamic processes, including climate change, sea level rise and water use. In such a setting, problems may easily be attributed to “natural” phenomenon such as reduced rainfall, thereby overlooking the contribution of human activities. Whether the urbanized deltas can successfully resolve problems of severe salt intrusion while at the same time fulfil future off-stream water requirements remains an important question for further investigation. By focusing on human water use, the study supports how integrated water resource management in the heavily urbanized delta regions can take up the challenge to confront severe salt intrusion and resulting water shortage.

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