WATER USE IN A HEAVILY URBANIZED DELTA

Scenario and Adaption Options for Sectorial Water Use in the Pearl River Basin, China

YAO Mingtian

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Abstract

Water use is increasing globally to meet the growing demand for food and industrial products, and the rising living standard. Water scarcity has been reported in many regions, questioning the long-term sustainability of water use. The objective of this thesis is to better understand sectorial water use development in an urbanizing river delta, and to explore the potential of water use management as an adaptation option to reduce water shortage. The Pearl River Basin in Southern China is taken as study area. The upstream part of the basin is one of the poorer regions of China, whereas the Pearl River Delta (PRD) is the world's largest urban region in both population and area. This study presents the first consistent analysis of sectorial water use in the PRD. Results show that during the period of 2000-2010, the PRD managed to stabilize its annual total water use. Nevertheless, severe salt intrusion induced water shortages occur. Assessment of water use at a monthly resolution shows that water use contributes to salt intrusion by further reducing the already low dry season river discharge.

To investigate the possible future development of water use, this study proposed a method to derive region specific water use scenarios from a global assessment of water use. Scenarios based on regionalised assumptions project substantially lower water use than those based on national assumptions. Nevertheless, hydrological challenges remain for the PRD. The total water use of the PRD may still increase by up to 54% in 2030 in the regionalized scenarios. Also, water use in the upstream regions increases with socio-economic development. To address water shortage, four extreme water allocation strategies were analysed against water use and water availability scenarios under climate change. None of these strategies proved to be sufficient to fully avoid water scarcity in the Pearl River Basin.

This study obtains a better understanding of the sectorial water use development and its impact on salt intrusion induced water shortage in a heavily urbanized river delta. The water use framework and methods used to derive regional water use scenarios are transferable to other regions, provided that data is available. Water use scenarios are crucial to sustainably manage water resources in a changing world.

Content

1

Chapter 1

Introduction

1.1 Fresh water resources

Freshwater is the most crucial element for life. But the total renewable water resource, i.e. the maximum theoretical amount of water available, is limited at around 54000 billion m^3, or at present global population numbers less than 8000m^3 per person for all the activities (GEO Data Portal 2010).

Moreover, this water does not remain constant, but continuously transfer through different stocks (lakes, soil, atmosphere, biomass, reservoirs etc.) and fluxes (river, rainfall, evapotranspiration, urban drainage etc.) within the hydrological cycle over various spatial and temporal scales. Some climates exhibit fairly even distributions of rainfall, e.g. the wet tropics and wet temperate climates, while in other climates it comes very uneven, e.g. in strongly monsoonal, Mediterranean or semi-arid climates. Consequently, the already limited fresh water resource is not available at the time and place where the water demand is. When water fluxes concentrate, or diminish at one place during a certain period, e.g. heavy rainfall, it could become a disaster. Thus, the actual distribution of water availability can be highly uneven and poses severe risks to human activities under temporary intensive rainfall or drought.

1.2 Anthropogenic water use

As the most crucial element for any human developments, the human body needs around 2.5 litres intake per day to maintain proper functions (Whitney and Rolfes 2016). Food production, energy generation, industrial manufacture and processing etc. are all heavily dependent on water resources. Anthropogenic water use has more than doubled during the past few decades (Yoshihide et al. 2013). During the period 1996-2005, it took 1385 m^3 fresh water per year on average to cover one person's demand of foods, goods and domestic uses (Hoekstra and Mekonnen 2012). That is a revision from Hoekstra and Chapagain (2007), when the number was only 1240 m^3 per year for the period 1997-2001. Not only the per capita water use increases, population growth is also a fundamental driving force causing rising water demands. During the period from 2001-2005, the world population grew by more than 5% (United Nations 2017).

When population grows, all the demands for foods, goods, energy, and services all increase, which leads to higher demand for water resources.

Urbanization, from many perspectives, is a positive process (Brand 2009). However, growing urban population also increases average prosperous and changes lifestyles. Consequently, not only the demands of energy, commodities and services rise, but also the consumption patterns change (FAOSTAT 2011), and so does the water demand (Lahart et al. 2008, Tietenberg 2003). For instance, the world average daily protein supply increased substantially from 61.40 g/capita in 1960s to 77.10 g/capita along with the population growth (FAOSTAT 2011). Increase in high (animal) protein consumption means higher feeds and fodder demands, i.e. water-intensive production, and higher water demand. Due to the changing lifestyle, global water use has grown twice the rate of population growth since 1900 (FAO 2010). It is estimated that world population will increase some 30% by the middle of this century, and reaches 9.3 billion (United Nations 2011). Fulfilling and sustaining water consumption is thus a crucial concern to achieve sustainable development.

Figure 1-1 illustrates the balance between fresh water resources and water uses in a river basin system, explicitly including an intra-basin competition over water resources between upstream and downstream. For a region in the middle or lower reaches of a river basin, the available water originates from direct precipitation, groundwater, and discharge from the upstream part of the basin. Water use consists of off-stream regional water use and allocations made for downstream water use and environmental flows.

Environmental flow requirements are even more crucial for the delta as, for instance, the river discharge must be large enough to suppress the salt intrusion, which may otherwise compromise fresh water inlets of the coastal cities. As can be seen from the figure, both water resource and water use could be affected directly or indirectly by climate change and socio-economic changes.

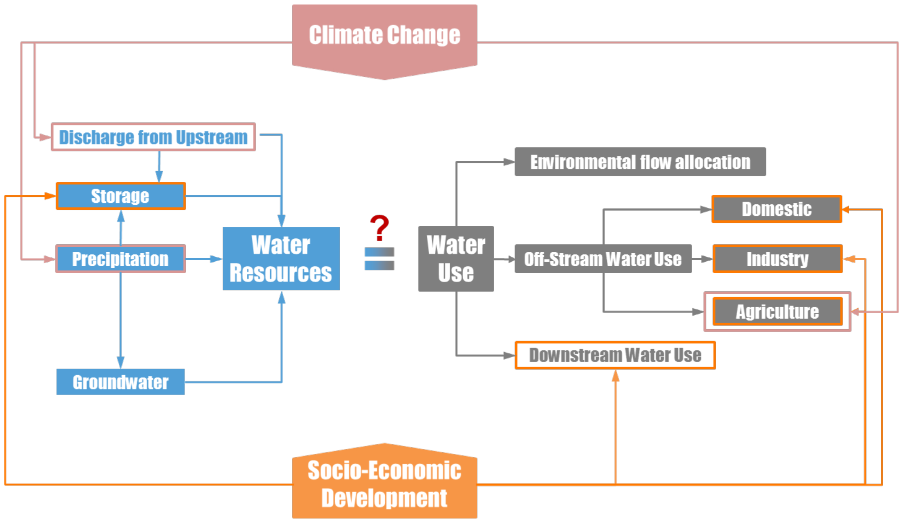

Figure 1-1. Water balance in the middle reaches of a river basin system. Blue boxes represent available water from various sources, grey boxes water requirements for various functions. When they are, orange outlined they are affected by socio economic developments, when pink outlined affected by climate change. White boxes with blue or grey fonts are not relevant at the watershed and in the delta respectively.

1.3 Climate change

Climate change is one of the great concerns in the current century. Climate change and sea level rise alter the hydrological cycle and its dynamics on global scales (Bates et al. 2008, Dore 2005, Kabat et al. 2004), as well as at local scales (Huang et al. 2004, Liu et al. 2009, Zhang et al. 2008). Changes in regional extreme weather and climate events lead to severe threats to humans and terrestrial ecosystem components on various spatial scales (Kabat et al. 2004). Climate change alters precipitation, evaporation, and stream flow dynamics, which in turn will have a significant impact on water resources. Moreover, due to the higher temperatures, anthropogenic water uses could increase for activities such as agriculture, manufacturing and domestic services. Thus, the future water security will not only be affected by changing water availability, but also by changing water use, which are both influenced by climate change. How climate change affects the anthropogenic water use is an important question to be answered.

1.4 Modelling anthropogenic water use

Generally, less effort has been put into the assessment of water uses than into the assessment of water availability (Döll and Hauschild 2002). Among the number of hydrological models that are developed to quantify the availability of water resources across different spatial and temporal scales, only few frameworks include well-established methods to assess water uses (Flörke et al. 2013, Hanasaki et al. 2010, Wada et al. 2011).

Anthropogenic water use is broadly categorized in three main sectors i) agricultural, which include irrigated crops and animal husbandry, ii) industry, which includes manufacturing and electricity generation, and iii) domestic water use, both private and public.

Agricultural water use, more specifically water used for crop production dominates the overall anthropogenic water use. The estimated global average annual water used for production was 9087 billion m^3 during the period 1996-2005, of which 8363 billion m^3 or 92% was used for agricultural production, 400 billion m^3 (4.4%) was used for industrial production, and 324 billion m^3 (3.6%) was used for domestic uses (Hoekstra and Mekonnen 2012). By 2050, the industrial water use is projected to have doubled compared to the water use in 2010, whereas the domestic water use is foreseen to increase 50% - 250% during the same period (Wada et al. 2016).

At the global scale, in general, water uses are described as function of the water used in producing a unit of goods or services (Alcamo et al. 2003a, Cai and Rosegrant 2002, Chapagain and Hoekstra 2008). At local scale, e.g. for a specific sector, data intensive water use models can be developed even for an individual user, i.e. specific water use can be described as a function of indicators of the production of a specific good or service (Arbués et al. 2003, Chen and Yang 2009, Fthenakis and Kim 2010, Shandas et al. 2012). Either way, the information about water use is not adequate for sustainable water resource management on regional scales. Because at the regional scale, availability of detailed data is often not sufficient to support the data intensive models, whereas the global integrated models are often too "coarse" to identify the regional specified characteristics.

Only few countries conducted comprehensive sectorial water use surveys that provide detailed and consistent information of water uses on a regional scale (Solley et al. 1998). Often, the available data can hardly reveal the development of sectorial water use and their corresponding driving forces over time. Therefore, it is unknown whether water is already a limiting factor to regional socio-economic development, especially in large and fast urbanising regions. Thus, modelling regional sectorial water use and its impact of socio-economic development first needs a comprehensive overview of how at this scale sectorial water use and its distribution changes over time.

Moreover, future management also requires water use projections to sustain livelihoods, well-being, as well as socio-economic development (UN-Water 2013). A recent multi-model assessment of future water use has established a consistent set of new global water scenarios based on the Shared Socio-economic Pathways (SSPs) (Vuuren et al. 2013) and the Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011), both being prepared in the context of the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC-AR5) (Moss et al. 2010). The question is, how to use the methods and information derived from global assessment in supporting the sustainable water resource management on regional scale. After all, the sustainable development needs to be achieved by each region.

1.5 The Pearl River Basin

Pearl River is a major water supply for agriculture, hydropower generation, navigation, industrial production, and drinking water in southern China (Cui et al. 2007). Pearl River has the second largest total discharge in China following the Yangtze River, whereas the Pearl River Basin (PRB) is the third largest river basin in China in area (Figure 1-2). The drainage area of the PRB is 4.54 x105 km^2 in total, of which 4.42 x105 km^2 is in China (PRWRC 2005). The Pearl River has three major tributaries: Xijiang river, Dongjiang river, and Beijiang river, of which Xijiang accounts for almost 80% of the total drainage area of the PRB and contributes most of the discharge.

The PRB is situated in the subtropical monsoon area. Most of the rainfall occurs during summer the wet season between April and September (Zhang et al. 2012). The annual average precipitation ranges from 1200mm to 2200mm. But the highly uneven spatial and temporal distribution of streamflow has caused seasonal water shortages in the basin (Zhang et al. 2009a).

Socio-economic development and water consumption also differ greatly across the regions in the PRB. The upstream basin consists of the poorest regions in China (Jalan and Ravallion 2000), whereas the delta is the world's largest urban region in both population and area (World Bank 2015).

The Pearl River Delta (PRD), located in Guangdong Province, southeast China, is the Pearl River estuarial region that includes nine major urban centres. During the period of 1988-1996, PRD experienced a scale of urban expansion unprecedented in the history of the country and the probably in the world. The urban area increased 364% from estimated 720 km^2 in 1988 to 2625 km^2 by 1996 (Seto et al. 2002). The cultivated area of Guangdong province, where the PRD is located, declined by 4000 km^2 from 1988 to 1993. But a bouncing back to the level of 1988 in 1996 suggested a remarkable landscape transformation extending agriculture system further into nature areas. The amount of agriculture land then peaked at 5.54 million ha in 1998, and reduced again gradually by 20% in 2008 (Guangdong Statistics Bureau 2016).

Figure 1-2. Location Pearl River and its delta

The Pearl River Delta is among the water rich regions in China with more than 1700mm average annual precipitation, and on average water availability per person in the delta is around double the country's average of 2200m^3 (Wang 2005). The Pearl River practically supplies all the water demands for food production, power generation, manufacturing and domestic uses (Pearl River Water Resources Commission 2015). Water gathered in the upstream catchments converge into the complex distributary systems and eventually drain through 8 river outlets into the estuary. The discharge however varies significantly from less than 4000 m^3/s in the dry season (winter-spring) to 28000 m^3/s in the wet season (summer-autumn), while during a flood event the peak discharge can exceed 40000 m^3/s (Hong Kong Environmental Protection Department 2009).

Nevertheless, the PRD is facing increasing severe water shortage events during the last decade (Tu et al. 2012). These shortages are primarily due to salt intrusion as the estuary topography is relatively flat, which allows the tidal motions to bring saline water into the delta river network (Cui et al. 2007).

The increasingly severe salt intrusion induced water shortages have instigated investigations on many aspects, include changes in discharge (Hu and Mao 2012, Kong 2011, Zhu et al. 2007), sand excavation (Han et al. 2010, Luo et al. 2006), sea level rise (He et al. 2012), wind direction (Li et al. 2009), and water management (Chen 2006a).

Chen (Chen 2006a) concludes that because the PRD is a water abundant region, water use management is neglected from the regional water management system. Therefore, to what extend the off-stream water use has its impact on salt intrusion, especially during the dry season thus further aggravating water shortages, is not clear.

Moreover, impacts of climate change have already been observed in both the PRD as well as the whole Pearl River Basin. Urban expansion warmed up the whole delta area by 0.07 ˚C of mean temperature and up to 0.9 ˚C over urban areas, comparing the landscape in the 1970s with the urbanized PRD in 2004 (Lin et al. 2007). Warmer urban areas increased temperature gradient to the ocean surface and enhanced sea breeze circulation (Lo et al. 2007). Precipitation is affected especially during the dry season (Kaufmann et al. 2007). Large scale landscape transformation in the upstream basin also affected the regional climate system and consequently water availability, although no clear trend or abrupt shift in annual water discharge has been observed in Pearl River Basin (Zhang et al. 2008), which indicates a more uneven distribution pattern of the seasonal water resource within a year. The whole basin has suffered up to 50 year return period droughts in 2004 and 2005 (Cui et al. 2007), while at the same time the annual flooded area and affected population during 1981-2000 period increased 2.94 and 13.62 times in comparison with the period from 1950 to 1980 (Chen 2006b). Moreover, further land degradation, water pollution, and an estimated sea level rise of 20 - 40 cm by 2030 put the delta area under more serious challenge of getting enough water resource (Huang et al. 2004, Zhu et al. 2002a).

Therefore, evaluation of the risks in water security associated with climate change and further socioeconomic development in the PRD is crucial to explore effective risk mitigation strategies and measures based on a scientific assessment of hydrological extreme events in relation to land use and water management.

1.6 Research objectives and questions

This thesis has two main research objectives:

1. *To quantify future sectorial water use development and water deficit in the PRD*
2. *To explorer strategies to adapt to the projected changes.*

Figure 1-3 illustrates the overall framework, system boundary, the major components and problems the present study issued.

The following chapters in this thesis answer four guiding research questions for the Pearl River Delta, which has been rapidly developed and heavily urbanized during the past few decades.

1. *What is the present situation of, and what are the major trends in sectorial water uses in the PRD, and how do they related to global water use models?*
2. *Does water use contribute to the salt intrusion induced water shortage, and thus can help alleviate the risks via management of sectorial water uses?*
3. *How to downscale the scenarios developed for global assessments to capture development of sectorial water use on a regional level?*
4. *How severe is the water deficit in the PRD in future? Can appropriate water resource management strategies alleviate the problem?*

The first two questions focus on the PRD's present water use, the drivers of water use and its contribution to reported water shortage events. The last two questions explore the possibilities that the water use can be sustained in the future by confronting water use and water availability under future climate change and socio-economic scenarios.

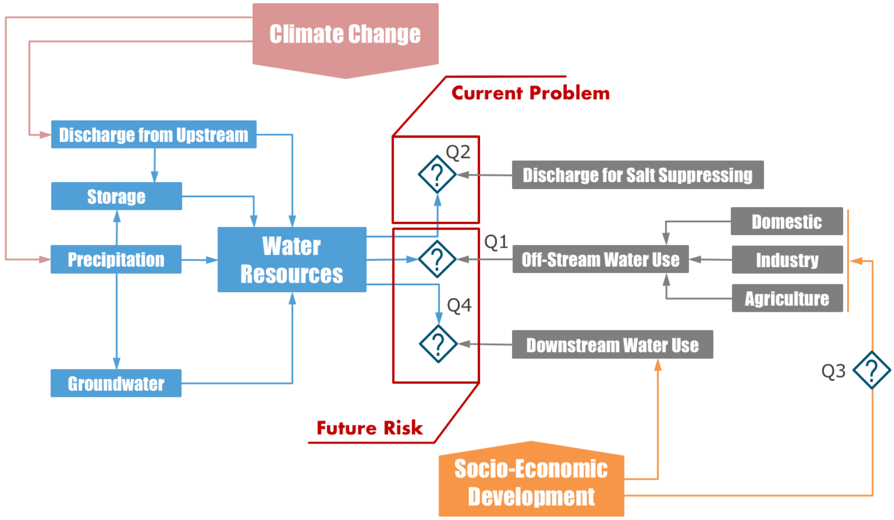

Figure 1-3. Framework of the present study. The four question marks (Q1-Q4) indicate the four research questions addressed in the respective chapters of this thesis.

Question 1: What is the present situation of, and what are the major trends in sectorial water uses in the PRD, and how do they related to global water use trends? (Chapter 2)

I address this question by exploring the driving forces underlying water use changes in domestic, industrial and agricultural sectors using the concept of water use intensity, and based on equations inspired by those used in global water resource models. The analysis is done at both the level of the region as a whole, as well as for the nine cities that constitute the PRD separately. I aim to find out whether water is a limiting factor to regional development, and how sectorial water use and its distribution changes.

Question2: Does water use contribute to the salt intrusion induced water shortage, and thus can help alleviate the risks via management of sectorial water uses? (Chapter 3)

The findings in Chapter 2 suggests the reported water shortage events can only be addressed at seasonal or monthly basis. Thus, I provide a more detailed analysis in Chapter 3. I select 5 cities within the PRD for in depth study. The contribution of sectorial water uses in causing severe salt intrusion is assessed by quantifying monthly sectorial water uses, and then comparing it with threshold discharges from the graded salt intrusion warning system for the period 2000-2010.

Question 3: How to downscale the scenarios developed for global assessments to capture development of sectorial water use on a regional level? (Chapter 4)

Understanding future water use at the regional level is crucial to assess sustainability. Against this background, in this chapter I attempt to address water use development for the near future up to 2050 on the regional level based on globally consistent socio-economic scenarios. I use two different downscaling techniques for developing regional water use scenarios, then investigate regional management requirements for the PRD.

Question 4: How severe is the water deficit in the PRD in future? Can appropriate water resource management strategies alleviate the problem? (Chapter 5)

Achieving the sustainable water resource management and river basin management requires combined efforts for water use and water availability. In this chapter, I project future water use for the whole Pearl River Basin. Then, together with my colleague, we confront water use with water availability to see whether the Pearl River Basin could obtain sufficient water to sustain its expected socio-economic growth under the changing climate. The water uses are projected under a regionalized socio-economic scenario set that is consistent with the scenarios used in recent global assessment.

In Chapter 6, I elaborate the principal findings in the context this thesis. I reflect on the methodological limitations and discuss implications for climate change adaptation and sustainable water resource management for the heavily urbanized delta region like the PRD. Finally, I provide recommendations for future research.

2

This chapter is based on:

Yao M, Werners SE, Hutjes RWA, Kabat P, Huang H. Sectorial Water Use Trends in the Urbanizing Pearl River Delta, China. PloS ONE. 2015;10(2):e0115039-e. doi:10.1371/journal.pone.0115039.

Chapter 2

Sectorial water use trends in the urbanizing pearl river delta, china

Abstract

Assessing and managing water use is crucial for supporting sustainable river basin management and regional development. The first consistent and comprehensive assessment of sectorial water use in the Pearl River Delta (PRD) is presented by analyzing homogenized annual water use data from 2000 to 2010 in relation to socio economic statistics for the same period. An abstraction of water use, using the concept of water use intensity, and based on equations inspired by those used in global water resource models, is developed to explore the driving forces underlying water use changes in domestic, industrial and agricultural sectors. I do this at both the level of the region as a whole, as well as for the nine cities that constitute the PRD separately. I find that, despite strong population and economic growth, the PRD managed to stabilize its absolute water use by significant improvements in industrial water use intensities, and early stabilization of domestic water use intensities. Results reveal large internal differentiation of sectorial water use among the cities in this region, with industrial water use intensity varying from -80 to +95% and domestic water use intensity by +/- 30% compared to the PRD average. In general, per capita water use is highest in the cities that industrialized first. Yet, all cities except Guangzhou are expected to approach a saturation value of per capita water use much below what is suggested in recent global studies. Therefore, existing global assessments probably have overestimated future domestic water use in developing countries. Although scarce and uncertain input data and model limitations lead to a high level of uncertainty, the presented conceptualization of water use is useful in exploring the underlying driving forces of water use trends.

2.1 Introduction

Global water use has grown at twice the rate of population growth since 1900, amongst others because of urbanization, industrialization and changing life styles (Watkins et al. 2006). By decreasing water retention capacity and water quality, cities reduce water availability. The expansion of urban areas transforms vegetated covers to sealed concrete surfaces. These changes increase surface runoff (Semadeni-Davies et al. 2008), alter the impact of precipitation on the water balance, change the fluxes of evapotranspiration and groundwater recharge, and thus affect surface hydrology and reduce water retention capacity in the urban area (Poelmans et al. 2010). In addition, cities discharge massive amounts of pollutants. Especially nutrients and sediments associated with domestic and industrial activities compromise water quality in both surface flows and groundwater (Groffman et al. 2003, Hatt et al. 2004, Paul and Meyer 2001, Walsh et al. 2005). At the same time, urbanization alters the temporal and spatial distribution of water uses by changing the population distribution and land use patterns. How to match changing water uses with water availabilities is therefore a key challenge for sustainable water resource management in any heavily urbanized region.

2.1.1 Assessing anthropogenic water uses

Less effort has generally been put into the assessment of water use than in assessments of water supply (Döll and Hauschild 2002). Anthropogenic water use is broadly categorized in three main sectors, i.e. agricultural, industrial, and domestic water uses. For any particular sector, rather data intensive bottom-up water use models have been developed, starting from individual users, in which the sectorial water use is often described as a function of indicators of the production of particular goods or services (Fthenakis and Kim 2010, Shandas et al. 2012). E.g., in the domestic sector, residential water use is simulated as a function of multiple household characteristics (Arbués et al. 2003, Chen and Yang 2009, Clarke et al. 1997, Mimi and Smith 2000, Voß et al.). The most common approach for industrial water use analysis estimates the overall industrial water use as a linear function of gross domestic product (GDP) or industrial value added (IVA), depending on the scale analysed, and other influencing factors (Seckler et al. 1998, Voß and Flörke 2010, Xiong 2005). Water use in thermoelectric power generation plants is mostly estimated as a linear function of actual electricity production (Fthenakis and Kim 2010, Inhaber 2004, Torcellini et al. 2003). A brief discussion of the relative definitions of water availability and supply vs water use and demand can be found in section 2.2.2, a more extensive discussion in Appendix B. In this paper, I adopt the term “water use”, pragmatically equating it to water supply and avoiding the much less knowable “water demand”.

At the global scale, sectorial water uses are generally approximated as a function of the water used in the production of a unit goods or services (Alcamo et al. 2003b, Cai and Rosegrant 2002, Chapagain and Hoekstra 2008). Several integrated global water resources assessments that use models based on above mentioned approaches utilized comparable schemes of global water uses. The global LPJmL (Lund-Potsdam-Jena managed Land) model (Bondeau et al. 2007) was elaborated by Jachner et al. (Jachner et al. 2007) with withdrawals for households and industry, in addition to water use by global irrigated and rain-fed agriculture. The global water assessment model “WaterGAP 2” (Alcamo et al. 2003a, b) for instance includes a global water use module capable of assessing current and future water use.

2.1.2 The objective of this study

On a regional scale, both data intensive sectorial water use models and large scale integrated water use models are of limited use. Data availability from, and consistency between different sources may be better at regional scales than at the global scale because of more uniformity in the statistical methods applied. But details, like household composition or technology selection of different industrial firms, are often not available to support the data intensive assessments. Only few countries conducted sectorial water use surveys that provide detailed and consistent information of water uses on a regional scale (Solley et al. 1998). The available data can hardly reveal the development of sectorial water uses and their corresponding driving forces over time, especially in large and fast urbanising regions. Whether water is a limiting factor to regional development often remains unknown, as comprehensive overviews of how sectorial water use and its distribution changes are lacking. Therefore, this paper addresses the following questions using the Pearl River Delta (PRD) as a case study:

- What is the present situation of, and what are the major trends in sectorial water use in the PRD?
- What socio-economic factors can explain these trends in water use?
- Can a region of this scale be considered homogeneous in these aspects, or do the cities differ in their development?

To answer these questions, I combine an analysis of homogenized available statistics (section 2.2.3) with a simple conceptualization of water use and its driving forces that consists of model equations originally developed for global sectorial water uses (section 2.2.4). Sectorial water uses on the regional and municipal scale can thus be analysed, while driving forces of sectorial water use can also be explored (section 2.3). Next, study limitations are discussed, followed by a discussion of the implications of our findings for the potential impacts of future socio-economic growth on water requirements (section 2.4). Finally, conclusions are drawn (section 2.5).

2.2 Materials and methods

In this section I describe the studied region, data collection and the proposed conceptualization of water use.

2.2.1 Study area

The PRD, located in Guangdong Province, southeast China (Figure 2-1), is the area surrounding the Pearl River estuary that includes nine major urban centres. During the past three decades, it experienced a scale of urban expansion unprecedented in the history of China (Seto et al. 2002). As can be observed in many delta areas in the world, recent urbanization development in the PRD area becomes more decentralized, from a single or very few large cities towards a more clustered network of cities that will "dwarf Great London by 26 times" [1](Gottmann 1964, Hall and Pain 2009).

The PRD is among the water abundant regions in China, receiving more than 1700mm average annual precipitation. The Pearl river supplies 95% of the fresh water required in the area (Pearl River Water Resources Commission 2015). Water from the upstream catchment area converges into a complex distributary system and eventually drains through eight river outlets into the estuary. The discharge of the Pearl River in the delta area varies significantly from less than 4000 m^3/s in the dry season to 28000 m^3/s in the monsoon season. During a flood event the peak discharge can exceed 40000 m^3/s.

[1] M. Moore and P. Foster, China to create largest mega city in the world with 42 million people, The Telegraph, 2011.

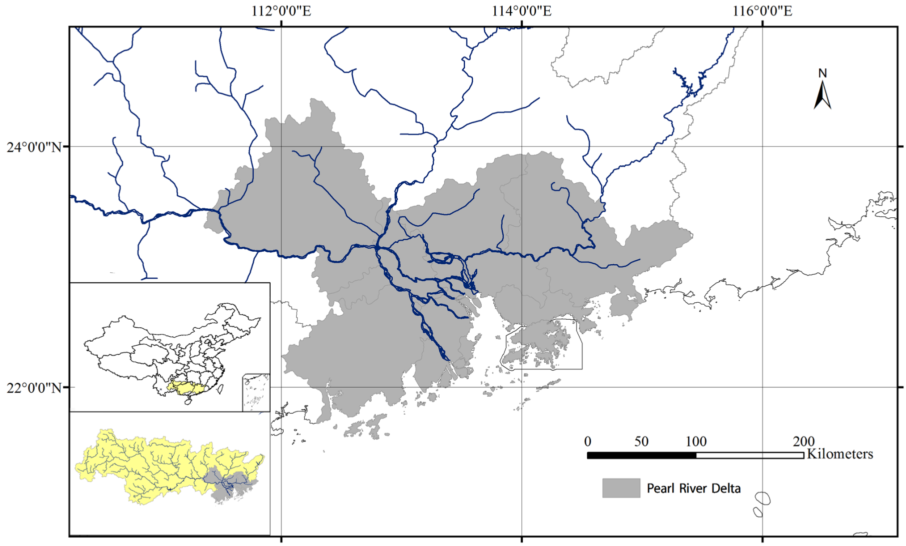

Figure 2-1. The Pearl River Delta. Maps at the lower-left corner show the location of the delta area in the whole Pearl River Basin, and where the Pearl River Basin is allocated in China.

Nevertheless, water shortage events have been reported more frequently during the last decade (Chen and Chan 2007, Chen 2006a, Tu et al. 2012). Recent studies indicate that the future water use of the PRD is expected to increase significantly (Guneralp and Seto 2008, Zhu et al. 2004), while at the same time the Pearl River Basin will likely become drier (Chen et al. 2009, Kaufmann et al. 2007). Water shortage appears to become a serious problem for this water abundant delta area (Huang et al. 2004, Zhu et al. 2002a).

2.2.2 System boundaries

To improve our understanding of the driving forces of the water use trends in the PRD, I reviewed the water resource system in the PRD within the following system boundaries.

As shown in Figure 2-2, the PRD water system includes different sources (upstream discharge, impoundment, precipitation and groundwater), and distribution flows (off-stream uses, eco-environment requirements, and direct discharge into the sea). Sea water utilization is also considered, as significant amounts of sea water are used in the region as cooling water for electricity production.

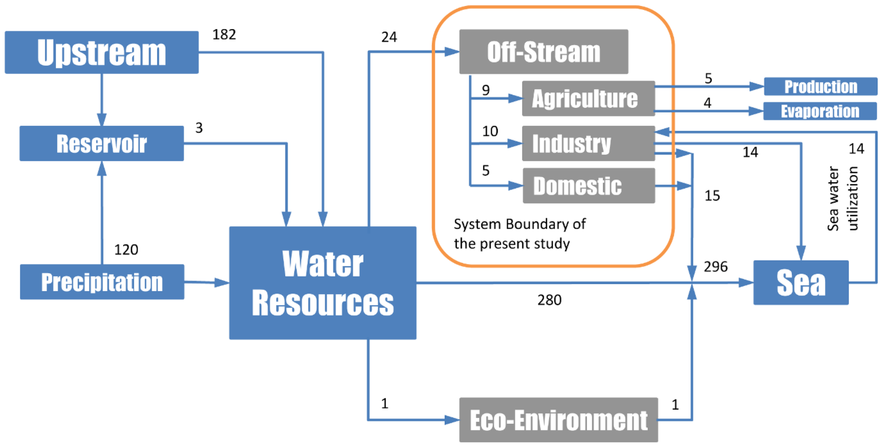

Figure 2-2. Water resource system of the PRD and the study boundary of the present paper. All the volume numbers are in units of km^3 (data source: Guangdong Water Resource Bulletin)

The present study focuses on the off-stream uses of the fresh water resource.

2.2.3 Data

The main sources of data collected for this study are listed in Appendix A.

The "Guangdong Water Resource Bulletin" (WB) is the main source for sectorial water use in the PRD since 2000. By using the five data quality indicators (DOIs) of the "Pedigree Matrix", I feel the selected data set is appropriate for our study, as it is from the appropriate time period and is collected specifically for the area studied (Weidema and Wesnæs 1996). However, the aspect of completeness is somewhat compromised as the sectorial water uses reported in successive bulletins are not directly comparable, mainly due to changes in the class definitions used in the statistics. Thus, the present study homogenizes the WB data to overcome the completeness issue and to obtain consistent trends of sectorial water uses.

Here a brief discussion of terminology is appropriate. An extensive discussion of the relative definitions of water availability and supply versus water use and demand can be found in Appendix B. The statistics report water withdrawn by, and/or supplied to the various sectors. Since no information is available on processing or conveyance losses, I equate these numbers to (actual) 'water use'. To assess present or future water stress, one would like to know 'water demand' the quantity needed for domestic or socio-economic activities; an amount that cannot always be met. Approaches to quantify demand generally are based on assumptions that relate this to a certain level and measure of economic development. However, exactly these assumptions can be questioned and may not hold when transferred from one situation (country/region, development stage) to another. This indeed is one of the main outcomes of the present study (see our results on domestic water use).

Only, a few major references in Chinese are cited in the main text as I deem appropriate. A more detailed explanation of the Chinese literature I used can be found in Appendix C.

2.2.4 Harmonization of Water Bulletin data

The WB includes annual amounts of water withdrawn by selected sectors and per capita or per unit of output water use intensity for each city in the PRD. However, only water uses in agriculture and industry sectors are reported in consistent categories throughout the study period. Statistical categorization of subpopulations of domestic water users were modified several times.

Table 2-1. Harmonized Sectorial Water Use in 10^8 m^3 (Original data can be found in Table D1 in Appendix D)

	Total	AGR	MAN	ELE	DOMU	DOMR
2000	212.9	97.1	-	-	29.2	-
2001	224.7	96.6	58.8	30.0	31.5	6.9
2002	236.4	93.3	-	-	34.7	7.5
2003	249.5	91.2	-	-	40.5	6.4
2004	258.3	89.4	85.0	27.8	46.7	5.6
2005	254.7	86.4	78.9	29.6	46.5	4.9
2006	247.0	83.0	79.5	28.3	51.8	5.1
2007	249.7	81.0	78.1	26.8	50.2	4.9
2008	246.4	81.6	73.3	32.5	48.7	4.9
2009	247.5	80.9	68.8	38.2	48.8	5.0
2010	236.1	74.9	70.6	30.6	48.9	5.2

Agriculture (AGR), Manufacturing Industry (MAN), Thermal Electricity Industry (ELE), Urban Domestic (DOMU), and Rural Domestic (DOMR).

To make the data comparable, I homogenized the WB data to yield total annual amounts of sectorial water use and the corresponding water use intensities for each of the nine cities. I first re-defined water use sectors, thereby separating the manufacturing industry (MAN) from the thermal electricity production (ELE), and grouping the multiple domestic classes into urban (DOMU) and rural (DOMR) domestic sectors, now also consistent over time. Water use volume and water use intensity are calculated then based on WB data and corresponding socio-economic data published. Table 2-1 and 2-2 present the homogenized data of sectorial water use and water intensity, respectively, over the period of 2000 to 2010. Detailed homogenisation steps are described in Appendix D.

Table 2-2 Harmonized Sectorial Water Use Intensity (Original data can be found in Table D3 in Appendix D)

	ITotal	IIND	IDOMU	IDOMR	IDOM-Total
	(m^3/person)	(m^3/104VA)	(l/day)	(l/day)	(l/day)
2000	496	289	269	-	-
2001	513	284	278	150	241
2002	535	264	296	169	261
2003	559	222	335	152	288
2004	572	168	374	139	317
2005	560	132	362	129	309
2006	521	106	377	146	329
2007	506	87	349	136	306
2008	480	71	323	133	286
2009	462	70	308	134	275
2010	420	53	288	148	264

2.2.5 Conceptualization of Water Use in the PRD

A simple conceptualization of off-stream water use and its driving forces is developed for the PRD that consists of equations reported for globally sectorial water uses. These simple equations are fitted to the harmonized data, to identify driving forces of water uses.

The socio-economic data have been documented more consistently and in greater detail for a longer period. The added value of our approach is that I can make use of these better reported socio-economic data to re-evaluate water use data. In addition, I lay a foundation for a model that can project future water use, assess future water use scenarios.

For each of the 9 cities, I assess fresh water use of four sectors, i.e. domestic (urban and rural separated, DOMU and DOMR), manufacturing industry (MAN), thermal electricity industry (ELE), and irrigation (IRR). In general, water use in every sector is expressed as a function of its driving forces and water use intensity. The total water use is expressed as:

$$W_{Total} = \sum W_i = \sum (I_i \times F_i) \tag{1}$$

where W is volume of water use, I_i is the water use intensity of sector i, and Fi is the driving force of that sector. The water use intensity I_i can be subject to economic, structural and technological changes, as described later. The driving forces Fi are published socio-economic data from the annual statistics (See Appendix A for data sources).

Domestic water use

I selected the equation from the global water use model WaterGAP2 and fitted it to each of the nine cities. Although the domestic water use can be simulated as a function of multiple variables such as water price, income, residential consumption and various household characteristics that may affect water use (Arbués et al. 2003, Chen and Yang 2009, Clarke et al. 1997, Mimi and Smith 2000, Voß et al. 2009), the data availability in the PRD is not sufficient to feed these data intensive approaches on household levels.

The approach of WaterGAP2 consists of two main concepts for calculating domestic water use intensity. Firstly, the structural change represents the change in water use intensity as result of the changes in the nature of water-using activities, e.g. behavioural changes or changes in the number of water using appliances (Alcamo et al. 2003a). It is represented by a sigmoid function:

$$I_{str} = I_{str-\min} + I_{str-\max} \cdot (1 - e^{-\gamma \cdot IN^2}) \tag{2}$$

A value of 50 l/person-day was used as the minimum requirement ($I_{str-min}$) (Gleick 1996). The maximal value ($I_{str-max}$) and the curve parameter (γ) are fitted to each city based on the historical data. The saturated structural water use intensity of the PRD is 430 and 180 litres per person-day for urban and rural respectively, where the corresponding γ is 0.005 and 0.041. Since GDP is normally published as the city average without differentiation between urban and rural sectors, per capita income (IN) of urban and rural resident are used instead to separate the urban and rural water use respectively.

The second concept, technological change, is assumed to always improve the efficiency of water use, i.e. decreases the water use intensity. The net domestic water use intensity can be computed by combining structural change and technological change as:

$$I_{DOM} = I_{str} \times (1 - \eta)^{t - t_0} \tag{3}$$

where I_{DOM} is the net domestic water use intensity, ŋ is the rate of technological improvements in water use efficiency. A 2% annual improvement rate based on German references from 1950 to 1995 is borrowed from the previous global assessment, as the GDP growth of the PRD during the study period is comparable with Germany in 1970s (Alcamo et al. 2003a).

The overall domestic water use (W_{DOM}) is then expressed as a product of per capita water use intensity (I_{DOM}) and population (POP) in the area:

$$W_{DOM} = I_{DOM} \times POP \tag{4}$$

Urban and rural water uses are separated into two sub-sectors since the observed state and trends of the two strongly differed during the studied period. Only the household water use is computed for the rural domestic sector (DOMR). For urban domestic (DOMU) the public water uses (construction and service industry) are included.

Manufacturing industry

The WaterGAP2 approach for industrial sector is not appropriate for the present study, as it includes fresh water withdrawn for electricity production in the overall industrial water use (Alcamo et al. 2003a). In the PRD, the manufacturing sector is comparable with the thermal electricity industry, accounting for about 25% of the total water use. Therefore, I separate them into two sectors.

It is difficult to develop a water use function that can represents all different manufacturing industries accurately in detail, even on smaller scales. Because different cities have different industrial structures (Appendix E), and the water use differs between various industries both quantitatively and qualitatively (Seckler et al. 1998, Voß and Flörke 2010, Xiong 2005).

I adopt a simple approach based on a previous study of industrial water use in China where manufacturing water use is computed as a product of the manufacturing water use intensity (I_{MAN}) and industrial value-added (IVA) (Xiong 2005). The manufacturing water use intensity is expressed as a function of per capita GDP and manufacture composition:

$$\ln(I_{MAN}) = b_0 + b_1 \times \ln(GDP_{ca}) + b_2 \times \ln(R_{HL}) \tag{5}$$

where GDPca is the annual per capita GDP, R_{HL} is the production ratio between heavy and light industry. The b0, b1 and b2 fitted for the PRD is 10.851, -1.733 and 1.194 respectively. The overall manufacturing industrial water use (W_{MAN})_is then expressed as a product of manufacturing water use intensity (I_{MAN}) and IVA of the city (Equation 6).

$$W_{MAN} = I_{MAN} \times IVA \tag{6}$$

Thermal Electricity Industry

Water used by the thermal electricity industry is computed by multiplying electricity production with a regional average water use intensity, I_{ELE}. The estimated I_{ELE} varied from 60-100 m^3/MWh during the study period due to restructuring of the sector (see Appendix A for data source). An average of 82 m^3/MWh is used.

I assume all the electricity in the PRD is produced by thermal power plants. Not all cooling systems need fresh water though. The volume of sea water utilized for cooling purposes in the PRD is subtracted from the result. However, the PRD-specific data about sea water utilization are being reported only since 2008. After 2008 67% of Guangdong's total seawater use for cooling occurred in the PRD. The same ratio is also applied to the period before 2008.

Irrigation

The consumptive irrigation water use is computed as the amount of water required by crops to be able to transpire at the optimal rate under the given climate conditions. Crop specific consumptive water use intensity I_c is computed following the FAO-56 approach based on 10-days intervals (Allen et al. 1998). Irrigation water withdrawal is then estimated with a local irrigation efficiency of 0.6 (see Appendix A for data source).

Daily meteorological data are gathered from 8 measurement stations in the area. Cultivation areas of 15 crops are collected for each of the nine cities. A PRD-specific paddy rice crop factor and the national average factors for vegetable, cash crops, banana and orange are listed in Table 2-3, 2-4 and 2-5 (see Appendix A for data source). For other crops the FAO suggested global average value are adopted (Allen et al. 1998). Vegetable, fruits and alfalfa are assumed to be grown all year around. Crop factors for these plants remain constant through the year.

Table 2-3 Monthly Crop Factors for Paddy Rice in the PRD Area

	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Early Rice	1.65	1.47	1.48	1.44	1.31				
Second Rice				1.41	1.16	1.37	1.54	1.53	1.33

Table 2-4 Crop factors for other cereals and cash crops

	Initial	Develop	Middle	End
Other Cereals	0.30	0.73	1.15	0.40
Tubers	0.50	0.80	1.10	0.95
Soybean-Spring	0.40	0.78	1.15	0.50
Soybean-Summer	0.40	0.78	1.15	0.50
Groundnuts-Spring	0.40	0.78	1.15	0.60
Groundnuts-Autumn	0.40	0.78	1.15	0.60
Sugarcane	0.40	0.83	1.25	0.75

Table 2-5 Crop factors for fruits, vegetables and green fodder

	Kc
Banana	0.90
Orange	0.79
Alfalfa	0.95
Vegetables & Melons	0.79
Other Fruits	0.75

2.3 Results

2.3.1 Sectorial water use

Figure 2-3 presents the homogenized sectorial water uses in the PRD during the period 2000 to 2010. On average about 24 km^3 fresh water was used annually. Industry (comprising manufacturing and electricity generation) surpassed agricultural water use in 2002, accounting for 43% of the total water use and remained rather stable afterward in both percentage and absolute amount. Agriculture water use gradually decreased from 9.7 km^3 in 2000 to 7.5 km^3 in 2010, accounting for 45% and 32% of the total respectively. Domestic water use increased by 5% relative to the total, from 3.8 km^3 in 2000 to 5.4 km^3 in 2010.

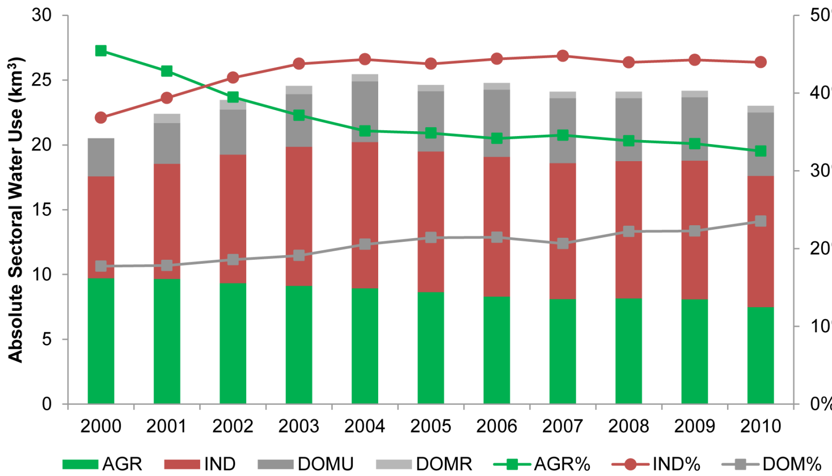

Figure 2-3. Sectorial water use of the PRD. Absolute (bars, left axis) and relative (lines, right axis) sectorial water use of agriculture, industry and domestic water use of the PRD reported by Guangdong Water Resource Bulletin.

2.3.2 Sectorial water use intensity

As shown in Figure 2-4, industrial water use intensity in the PRD is decreasing, while water use intensities remained rather stable in the rural, domestic and irrigation sectors. Urban domestic and the overall per capita water use intensity share a similar trend that peaked in 2004 and gradually decreased thereafter. On average, people consumed 288 litres of water per day for domestic uses. The industry sector needed on average about 160 m^3 of water to produce 10000 Yuan of IVA. Crops required 11500 m^3 per ha for irrigation. In total, an average of about 500 m^3 of water was used per capita in the PRD during the studied period.

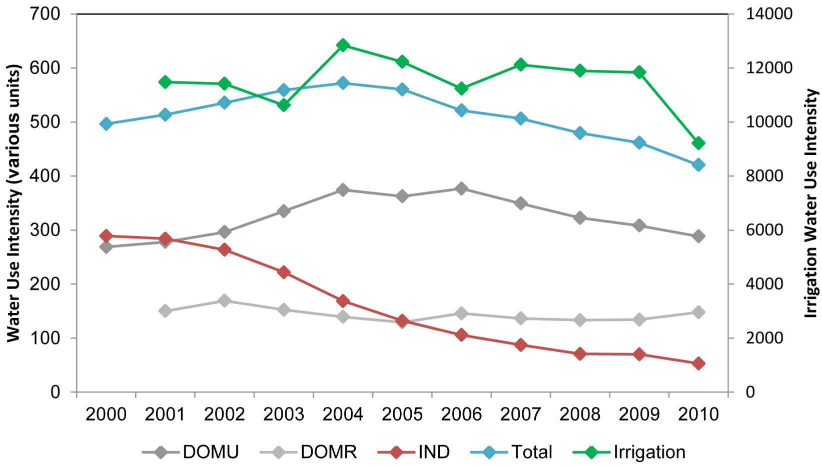

Figure 2-4. Water use intensity in the PRD. Values shown are in the units of litres/person-day for DOMU and DOMR, m^3/104 Yuan IVA for IND, m^3/ha for IRR, and m^3/person-year for the Total water use intensity (Total) respectively.

2.3.3 Exploration of driving forces

The conceptualization of water use was developed to get better insights and understanding of the underlying driving forces of water use development in the PRD. It allows us to use better documented socio-economic data evaluate water uses during the studied period.

Results of absolute volume and intensity of the sectorial water uses in comparison with the homogenized WB records are presented in Figure 2-5 and 2-6 respectively. The conceptual framework with globally reported sectorial water use equations explains well the sectorial water uses with the selected socio-economic variables as listed in Table 2-6 for the studied period.

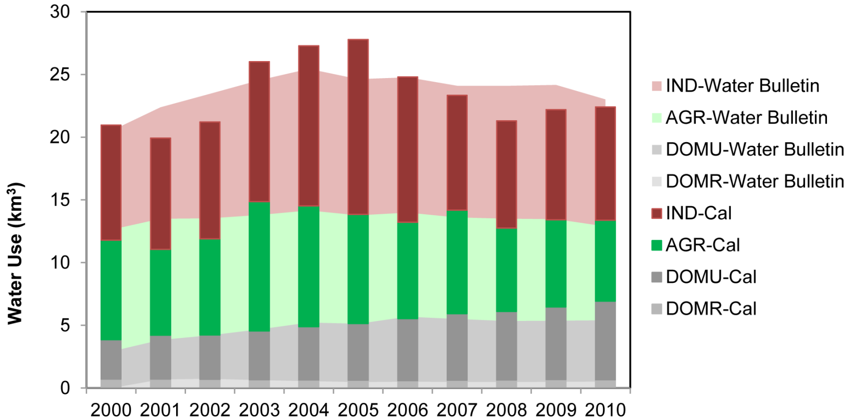

Figure 2-5 Sectorial water use comparison between calculated results and WB reported data

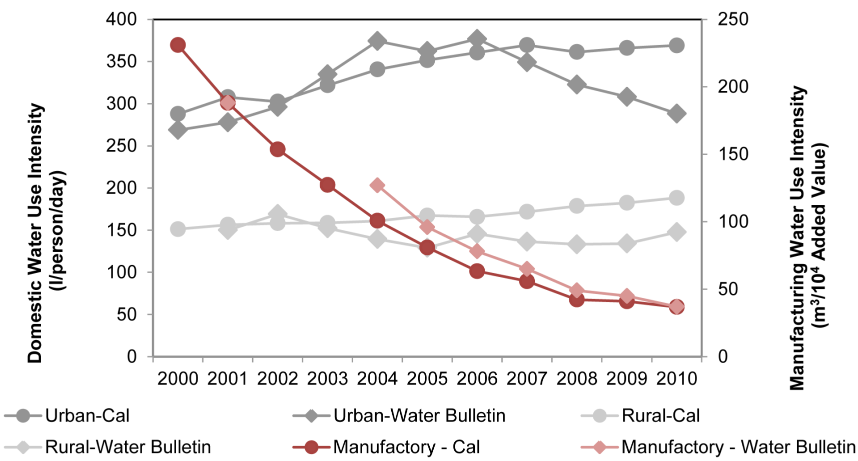

Figure 2-6. Comparison of domestic and manufacturing water use intensity between calculated results and WB reported data

The levelling off trend of the urban domestic water use intensity was well reproduced by income. The calculated rural water use intensity increased gradually following the income, but a rather stable trend was recorded.

Table 2-6 Socio-economic development in the PRD

	Population	Urban Population	Rural Population	IVA	R_{HL}	GDP per capita	Cultivation Area
	10^4 person	10^4 person	10^4 person	10^8 Yuan		Yuan	ha
2000	4,290	2,981	1,309	2,724	98%	18,815	732,701
2001	4,376	3,109	1,268	3,128	104%	20,295	719,500
2002	4,415	3,205	1,210	3,763	105%	22,657	688,618
2003	4,464	3,312	1,151	4,841	114%	26,292	657,420
2004	4,517	3,421	1,095	6,695	114%	30,866	761,667
2005	4,547	3,516	1,031	8,217	126%	36,118	634,379
2006	4,737	3,769	969	10,188	131%	41,774	559,291
2007	4,931	3,937	994	12,020	128%	47,892	622,056
2008	5,138	4,134	1,004	14,954	131%	53,310	687,015
2009	5,362	4,337	1,025	15,286	128%	54,789	598,254
2010	5,616	4,646	970	19,080	129%	61,757	524,247

Domestic water use intensity in the PRD shows a similar trend as in the global assessment, as shown in Figure 2-7 (Alcamo et al. 2003a). Results for the better developed urban sectors correspond to the levelling off or stable part of the curve, suggesting the urban domestic sector has reached its saturation water use intensity, and should remain stable or even start to decrease as is suggested by trends observed in global assessments. But I failed to reproduce the significant decline after 2006. Results for the rural domestic sector correspond to the steep part of the curve, which implies that in rural areas water use intensity may still grow sharply with income increases.

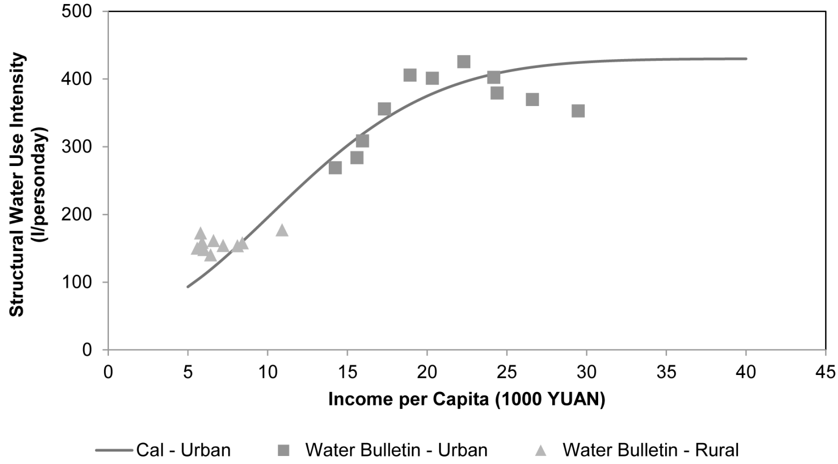

Figure 2-7. Structural water use intensity in the domestic sector in the PRD. Comparison between calculated results and WB reported data

The presented conceptualization also explains well manufacturing water use intensity, as shown in figure 2-6, with per capita GDP growth, manufacture composition, and IVA.

2.3.4 Internal differentiation

Figure 2-8 illustrates the relative size of sectorial water use in the different cities and the whole PRD. The nine cities show substantial differences. Guangzhou, which is the capital of the area and inhabits more than 20% of the population of the PRD, accounted for one third of the total water use. It was the dominant water user for industry and urban and rural domestic sectors, accounting for 51%, 29% and 21% of the total on average respectively. Jiangmen was the largest agricultural water user accounting for 22% of total agricultural water use.

Water use intensity show significant differences as well between cities, especially in the manufacturing and domestic sectors. In general, domestic water use intensity was higher in the cities that industrialised early. Guangzhou citizens consumed the most among the nice cities with 386 litres of water per person-day, whereas people in Zhaoqing required 226 litres only. Since 2008 Zhuhai has surpassed Guangzhou requiring the most water for per capita urban domestic use.

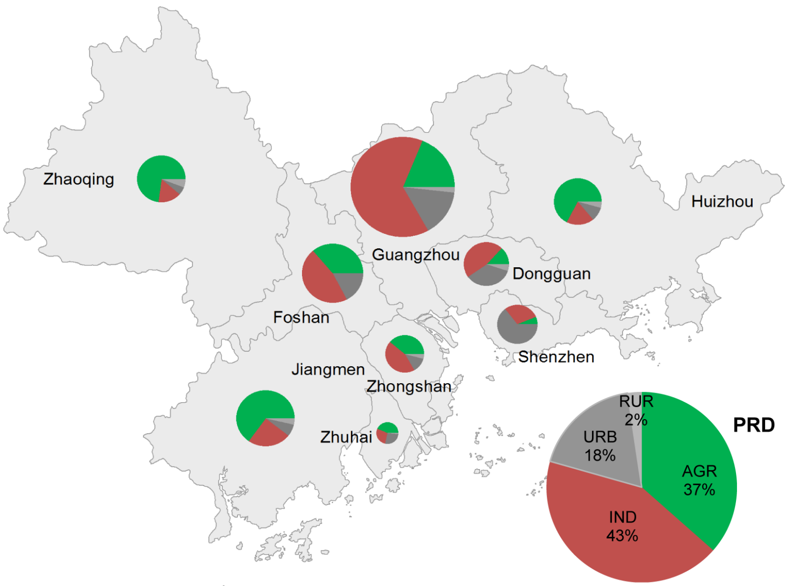

Figure 2-8. Sectorial water use of different cities in the PRD. Size of the pie chart indicates the average total water use level of the city over the study period. Areas of green, red, dark grey and light grey represent the proportion of agriculture, industry, urban domestic and rural domestic water uses respectively.

The nine cities also had varying saturation water use intensity during the studied period as can be seen in Table 2-7. Guangzhou required the most at more than 530 litres per person-day, which was comparable to the maximum recorded for the United States and European countries (Flöerke and Alcamo 2004, Shiklomanov 2000). Zhaoqing however had much lower value of 300 litres per person-day only.

Before 2003 Guangzhou required most water per person-day in the rural domestic sector. Since then it dropped significantly. Rural domestic water use intensity showed a downward trend in most cities. Dongguan, however, showed a significant increase from 83 litres per person-day in 2000 to 254 litres in 2010. No rural domestic water use occurred in Foshan and Shenzhen since 2002 as the two cities are fully urbanized.

Table 2-7 City differentiation of domestic water use parameters, referring to equation 2. Subscript UR means parameters for urban domestic sector; RU means parameters for rural domestic sector

City	γ_{UR}	$I_{str\text{-}max\text{-}UR}$ l/person-day	R^2_{UR}	γ_{RU}	$I_{str\text{-}max\text{-}RU}$ l/person-day	R^2_{RU}
Dongguan	0.003	440	0.847	0.008	260	0.866
Foshan	0.006	330	0.761			
Guangzhou	0.005	530	0.392	0.017	290	0.228
Huizhou	0.007	310	0.870	0.084	130	0.583
Jiangmen	0.008	370	0.758	0.033	140	0.749
Shenzhen	0.002	430	0.865	0.015	150	0.995
Zhuhai	0.005	400	0.841	0.043	130	0.569
Zhaoqing	0.011	300	0.956	0.100	120	0.403
Zhongshan	0.005	380	0.670	0.020	210	0.073
PRD average	0.005	430	0.855	0.041	180	0.601

Looking at the water use for irrigation, Zhuhai, Dongguan and Shenzhen show remarkably lower intensities than the PRD average. Irrigation water use per ha in Dongguan was less than 6700 m^3, followed by Zhuhai and Shenzhen with less than 8000 m^3. Irrigation systems in the other cities required more than 10000 m^3/ha of water. The average irrigation water use intensity in the PRD during the studied period was 11490 m^3/ha.

With respect to industrial water use required to produce 10000 Yuan IVA, the nine cities showed great diversity in 2000. The manufacturing industry in Zhaoqing required 1073 m^3, which is 25 times the 42 m^3 for Shenzhen. All the cities exhibited remarkable improvements of the manufacturing water use intensity afterwards. By 2010, the average amount of water used in the manufacturing industry to produce 10000 Yuan IVA was 58 m^3 in the PRD. Shenzhen had the most water effective manufacturing industry requiring 12 m^3 only, whereas Guangzhou showed the highest value of 114 m^3. Table 2-8 shows the curve parameters (b0, b1, b2) fitted for each of the nine cities based on historical water uses. As can be seen, the manufacturing structure (b2) had significant influence on water use intensity in the earlier industrialized cities such as Guangzhou and Zhaoqing, whereas a newly established city like Shenzhen was mostly affected by the economic development (b1).

Table 2-8 Parameter fitting for the manufacturing water use calculation, equation 5

City	b0	b1	b2	R^2
Dongguan	7.957	-0.971	-0.480	0.953
Foshan	9.313	-1.419	0.284	0.950
Guangzhou	17.865	-3.363	2.326	0.991
Huizhou	3.363	0.356	-0.435	0.572
Jiangmen	10.885	-1.826	1.562	0.903
Shenzhen	7.803	-1.130	-0.033	0.944
Zhuhai	6.410	-0.677	-0.497	0.933
Zhaoqing	10.021	-2.107	1.755	0.801
Zhongshan	7.472	-0.787	-0.002	0.968
PRD average	10.851	-1.733	1.194	0.992

Figure 2-9(a) shows the highest and the lowest manufacturing water use intensity at city level and their development in comparison with the PRD average, whereas Figure 2-9(b) presents the absolute volumes of water used. Regardless of the significant improvement of the intensity, the absolute volume of manufacturing water use remained rather stable for all cities, due the fast-economic growth.

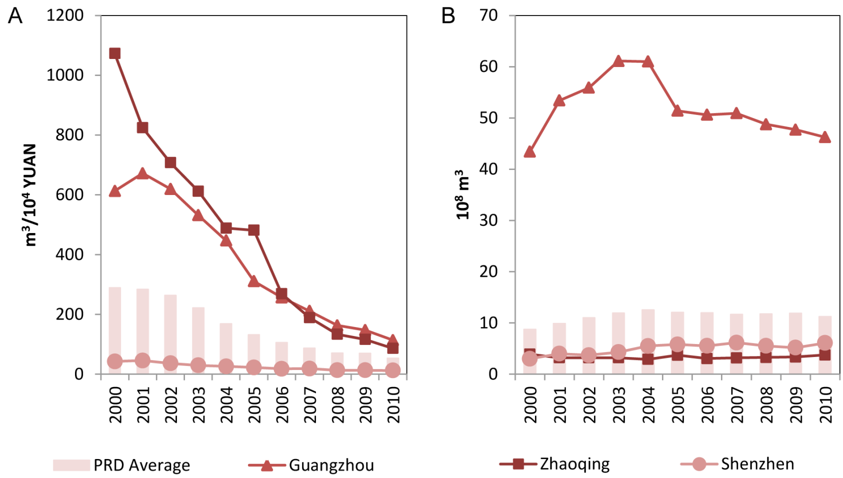

Figure 2-9. Internal differentiation of water use in the manufacturing sector in the PRD. Figure 2-9A is the internal differentiation of the manufacturing water use intensity. Figure 2-9B is the internal differentiation of absolute volume of manufacturing water use.

2.4 Discussion

In this study, I present the first consistent and comprehensive assessment of water use in all cities of the PRD. Previous local studies estimated sectorial water use by assuming typical per-capita intensities that were either depend on the size of the city (He et al. 2006), or a single average value as the baseline with fixed growth rate (Zhu et al. 2002b). In our conceptual framework, city-specific water use data and corresponding socio-economic figures are linked by selected globally reported model equations.

2.4.1 Uncertainties from water use data

The water use dataset collected from the Water Bulletin is in general well documented. By checking with the Pedigree Matrix, data quality regards to reliability and geographical correlation are both very high. Due to the compromised completeness, I performed harmonization to mitigate the uncertainties.

As a consequence of the change in reporting of census data, the urban per capita water use intensity may be overestimated, while the rural figure may be underestimated. The “HuKou” registration system in China, which manages people in their birthplace rather than place of residence, results in underestimation of urban populations by ignoring migration labourers. It is also unknown whether the absolute volume of water use by this “ignored” population was considered, as it was not specified in the statistics before 2003.

Lack of data also caused uncertainties in the calculated results, especially for the industrial sector. The thermal electricity industry is poorly represented. Both absolute volume and intensity of water use in this sector were hard to access, as were the details about the thermal power plants, e.g. type of cooling system, or technology adopted. Calculations based on an average provincial water use intensity quota thus may have overestimated water use, as the better developed delta area may have adopted more efficient cooling system than the provincial average. Elaboration of the water use estimation in electricity production sector will require more details about the configuration of power plants in the PRD and their use of sea water vs fresh water for cooling.

In addition, issues such as illegal withdrawal are not considered in our study because of lack of data. Water use will be underestimated if unregistered rural domestic and industrial withdrawal occurred.

2.4.2 Uncertainties from socio-economic yearbooks

The published IVA includes only the enterprises above a certain threshold which account for around 83% of the total industrial value added in 2000 to above 90% in 2010. The total amount of manufacturing water use may be underestimated due to the incomplete IVA data. More in general, the regional water use of the industrial sector and the relevant impact factors are still poorly understood due to the complexity of industrial structure, scale, technological development and policy.

2.4.3 Comparing to previous global water use assessments

As WaterGAP2 suggests, while income increases, the simulated structural water use intensity levels off, depending on the saturation value selected. Previous global assessment with WaterGAP2 suggested that for developing countries a saturation value comparable with the United States and Europe should be adopted, as these regions are expected to follow the same development trajectory and finally reach a comparable maximum intensity (Alcamo et al. 2003a). However, the reported water use intensities for most PRD cities do not support this scenario, and large internal differentiation exists. The average saturation structural water use intensity of the PRD is significantly less than the values used in global assessment as about 425 litres per person-day as shown in Figure 2.7. City-specific values varied from 300 to 530 litres where early developed cities like Guangzhou have much higher values than recently developed cities like Zhaoqing.

One probable reason for such differentiation between PRD cities is that households in later developed cities started with more sophisticated water use appliances and technologies and are supported by a better supply system. As reported by Chu et al. (2009), water use appliances have different diffusion paths among households along with the income growth. Appliance replacement has its impacts on water use intensity. This implies the parameter $I_{str\text{-}max}$ in the Equation 2 should not be set to a global constant, but requires location-specific historical records.

Recent elaboration of WaterGAP2 also reported similar differentiation on saturation value for European countries (Flöerke and Alcamo 2004). Our study confirms that differentiation exists not only among countries, but on smaller scales as well. Fast developing delta areas like the PRD are unlikely to reach domestic water use intensities as high as the global assessments suggested. Water requirement scenarios for the domestic sector in developing countries are very likely overestimated in previous global assessments.

In comparison with the most recent global estimation, manufacturing water use intensity in the PRD of about 67 m^3/1,000 US$2000 IVA was already better than 86 m^3 of the Asian-Pacific average. Nevertheless, although the water use intensity was reduced by half over the studied period, the level of 30 m^3 in 2010 was still much higher than the North American value of 19 m^3 in 2005 (Voß and Flörke 2010).

With regards to the electricity generation sector, the 82 m^3/MWh intensity used for the present study is still higher than the up-to-date once-through system of 76 m^3/MWh. The most water efficient cooling pond requires only 1.1 m^3/MWh (Fthenakis and Kim 2010).

2.4.4 Study Limitations and Outlook

The temporal correlation aspect of data quality is bit compromised as the water use data are available for only ten years, which limited our study period no earlier than 2000s. Ideally our study may provide more comprehensive results if the data could support an analysis for the last 30 years, because the PRD started its economic booming since late 1970s. Also, longer time series might have allowed a separation of parameter fitting and their validation to different subsets, i.e. sub periods of the data, an approach I believed of limited use within the current dataset limitations. Also, the reported strong differentiation between cities did not leave room for validating parameters found for one city to be validated at another.

Reasons for the mismatch in domestic water use intensity between calculated results and reported data after 2006 may be caused by the fact that the domestic water use equation of WaterGAP2 does not include any explicit parameter representing water savings, e.g. due to water pricing and public awareness improvement. Apparently, the rate of technological improvements in water use efficiency (η in equation 3) cannot represent such factors as the policy changes induces a stepwise improvement at such small scale, rather than a more gradual improvement as a policy disperses through a large country. Factors such as policy regulation and raising public awareness should be included, as central administrative measurements have strong impacts in China. Public awareness and habits of water saving as the results of recently promulgated laws and regulations significantly improved domestic water use intensities since 2003 (He et al. 2006).

Manufacturing water use intensity differs strongly between the PRD cities due to the diverse industrial structure and historical development. Take Guangzhou and Shenzhen as example: the IVA of these two cities was similar in 2000 at 70 billion Yuan. But the water use intensity of Guangzhou was 15 times larger than that of Shenzhen. Statistics show that heavily water dependent manufacturing industries such as chemical materials, textile and petroleum accounted for more than 40% of gross output value of the Guangzhou industry. While 40% of the gross output of Shenzhen industry was generated by electronic equipment production. The high-tech industry was selected as the economic engine for Shenzhen for the new special economic zone set in 1978, when China launched the reform and opening-up policy, which resulted in a low industrial water use intensity from the very beginning of its development. I suggest further analyses of the impact of different industrial development trajectories on water use in the future.

Both WB water use data and calculated results suggest that on the annual scale water use in the PRD is well managed without considerable shortages. Yet, severe seasonal water shortages have been reported due to temporarily unevenly distributed water resources in the delta area (Q. Chen, Half the Guangdong Municipalities Encountered Water Shortage, Nanfang Daily, 2010). Water shortage caused jointly by drought and salt intrusion requested 843 million m^3 of fresh water from upstream reservoirs to relieve the stress in 2005, followed by 550 million m^3 in 2006, which is equivalent to about one sixth of the annual urban domestic water use. Such events indicate that the water resource management system in the delta area is vulnerable to changes in the hydrological regime. Achieving sustainable water management in the PRD will require more insight in seasonal fluctuations in future studies. Furthermore, as water use is only part of the water resource management, to better understand the water scarcity in the PRD from a systematic perspective, a full life cycle analysis (LCA) on water resource could be very helpful. Recent works on cascading effects within a single river basin (Loubet et al. 2013) and environmental impacts from different components of the entire urban water system (Lemos et al. 2013) provide good examples.

2.5 Conclusion

Analysis of homogenized observation data and the presented conceptualization of water use provided the first consistent and comprehensive assessment of sectorial water use across the nine cities in the PRD during the period of 2000-2010. The homogenized sectorial water use volumes and intensities revealed clear trends in water use in the PRD. The conceptualization of water use offers the advantage to explore insights of driving-forces of such trend by linking reported socio-economic data with annual water use data.

On average about 24 km^3 fresh water was used annually in the PRD. Industrial water use surpassed agriculture and became the dominant water user in 2002, accounting for 43% of the total water use.

Large internal differences exist between cities. In general, the early developed cities have higher domestic water use intensity. Per capita water use in all cities except Guangzhou reached a saturation value much below what is suggested in recent global studies. Thus, the current global outlooks may overestimate domestic water demand for developing countries.

Water use in the manufacturing sector showed even larger differentiation between cities due to a great diversity of industrial structure, scale, technologies and policy decisions. City like Shenzhen selected high-tech manufactures to be the pillar industry from the very beginning of its industrialization. Consequently, its manufacturing water use intensity is found to be much lower than in other cities.

Despite the fast growth in economy and population, the PRD managed to stabilize its absolute water use by improving water use intensities. Nevertheless, temporary shortages occur. To better understand the temporal and spatial distribution of water use and potential shortages, it is important to have more insights on monthly resolution and to catch the complexity of manufacturing sector at the regional level. Finally, the impact of water related regulations and improvement of public awareness should be considering to assess whether fresh water will become a limiting factor for socio-economic development in the PRD.

3

This chapter is based on:

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Chapter 3

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

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.

3.1 Introduction

Water shortage is one of the major challenges of this century (Falkenmark et al. 1997, Postel et al. 1996, Vörösmarty et al. 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 et al. 2012, Cornforth 2012, Islam et al. 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 et al. 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 et al. 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 et al. (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 and 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 (Zhang et al. 2009b, Zhang et al. 2008), or even to show significant increases in dry season (Chen et al. 2012, Zhang et al. 2009c).

Other factors, which could enhance salt intrusion have also been studied, such as sand excavation (Han et al. 2010, Luo et al. 2006), sea level rise (He et al. 2012), and wind direction (Li et al. 2009). Only Chen (2006a) discussed water use and management aspects.

Chen (2006a) 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, I confirm that on annual time scales the PRD has enough water supplies to fulfil its water use2 (Yao et al. 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 3.2.1). 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 3.2.2). A conceptualization of off-stream water use previously developed for the PRD was then elaborated to allow the monthly sectorial water use analysis (Section 3.2.3). Influence of monthly sectorial water uses on salt intrusion thus can be assessed, while the current and potential improvement strategies can also be tested (Section 3.2.4). Next, results are presented (Section 3.3). Then, practical implications of findings are discussed (Section 3.4.1), followed by a discussion of the uncertainties (Section 3.4.2) and study outlook (Section 3.4.3). Finally, conclusions are drawn (section 3.5).

[2] 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).

3.2 Materials and method

3.2.1 Study area

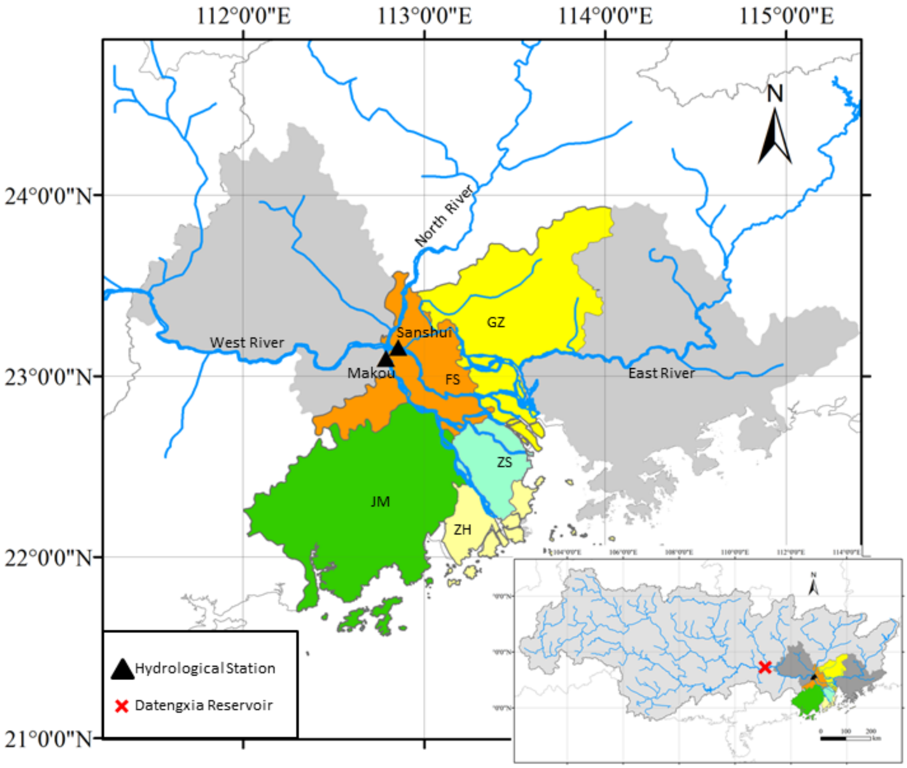

Figure 3-1. Study area of the Pearl River Delta. Shown are the 5 municipalities Guangzhou (GZ), Foshan (FS), Zhongshan (ZS), Zhuhai (ZH), and Jiangmen (JM) of the PRD (include the dark grey areas) and the two discharge stations, Makou and Sanshui that measure the total inflow to the delta from the West 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 3-1). 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 2016). 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 (QSD), which typically varies from less than 2000 m^3s-1 in the dry season (winter-spring) to 32000 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 contribute 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 et al. 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 QSD significantly correlated with the daily average salinity-over-standard period in the main PRD distributary channels (Wen et al. 2007). As a result, a graded salt intrusion warning system was established (Wen and Yang 2006). The warning system defines five alerting QSD levels (Q_{ASD}), each corresponding with a different impact of salt intrusion. I adopted these Q_{ASD} levels as indicators to assess the possible impact of salt intrusion under given hydrological conditions. Table 3-1 and Figure 3-2 show how the inland fresh water inlets may be affected by salt intrusion when QSD decreases.

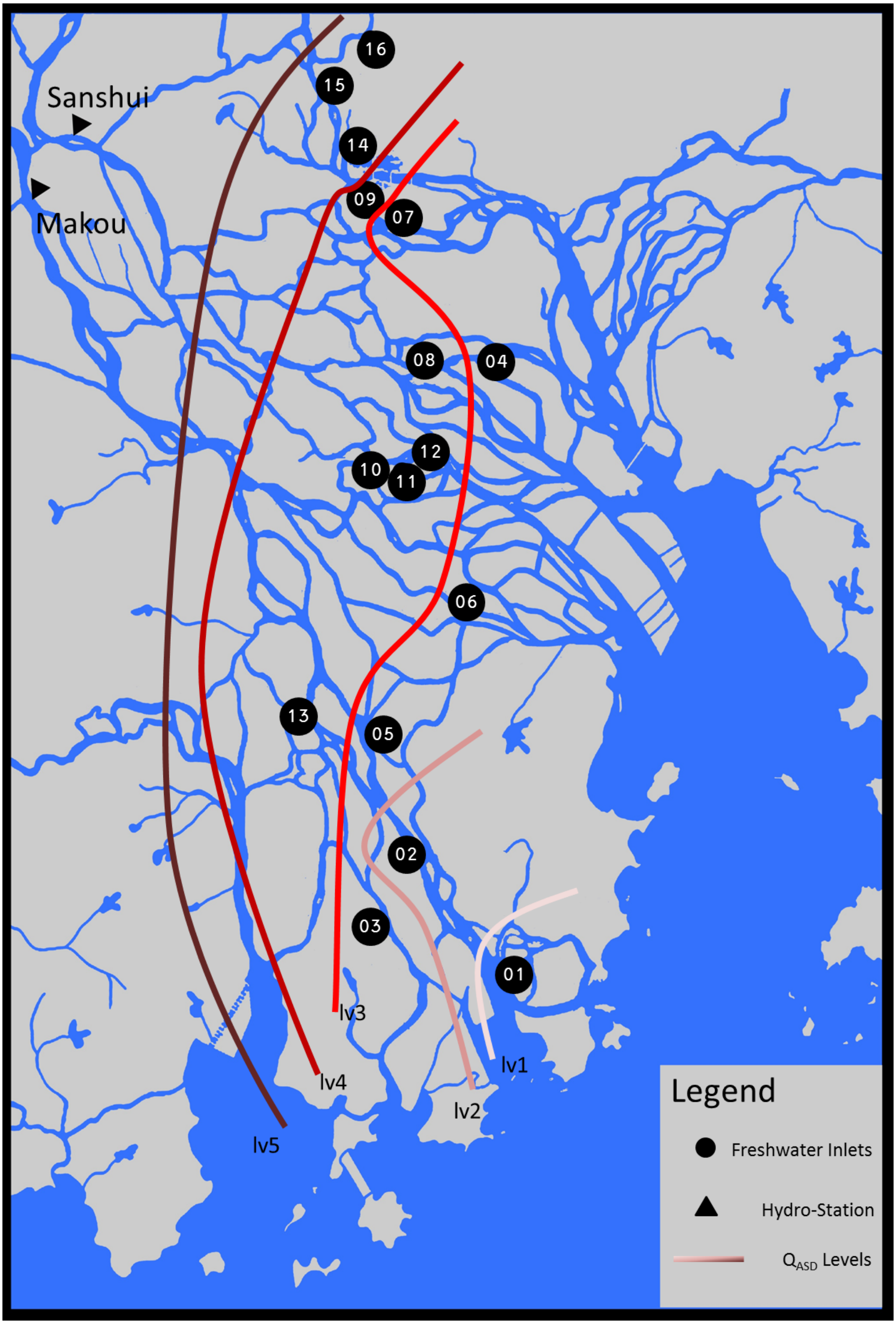

Figure 3-2. Possible impact of salt intrusion associated with Sixianjiao Discharge alert (Q_{ASD}) levels. The pink to purple lines indicate the limit of salt intrusion associated with progressive Q_{ASD} levels. The numbered dots are major water abstraction points. Note the lines in the graph indicate the salt intrusion warning levels only, rather than the actual salinity contour line.

Table 3-1. Salt intrusion warning system based on Sixianjiao discharge alert (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

3.2.2 Data

Two sets of literatures 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 2016). 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 Province3 (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.

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

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 Meteorological Information Centre4 and socio-economic data from the regional statistic yearbooks (Guangdong Statistics Bureau 2016) were collected as drivers to compute the sectorial water uses. No meteorological data was available for Zhuhai specifically. Data from Macau5 were used as the two cities are in the same area.

3.2.3 Monthly water use

I 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.

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.

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 IMAN 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}.

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

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

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 3.2.2).

3.2.4 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 (Liu et al. 2010). 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 and Zhu 2010), thus help resolve the salt intrusion problem for the future (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 sectorial 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 intensity (53 m^3 per 10,000Yuan VA_{MAN} in 2010) was reduced to the level of Germany6 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.

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[6] Source : EUROSTAT

This similarity implies that in principal, the PRD could be able to decrease the manufacturing water use intensity 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 and Steward 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 Bangladesh4, 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 intensity in the MP scenario was set to 115 litres per person-day, the average value of the EU4 in 2010, compare to an average 264 litres per person-day for the PRD in 2010.

3.3 Results

3.3.1 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.

3.3.2 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.

3.2.3 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 3-3, 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.

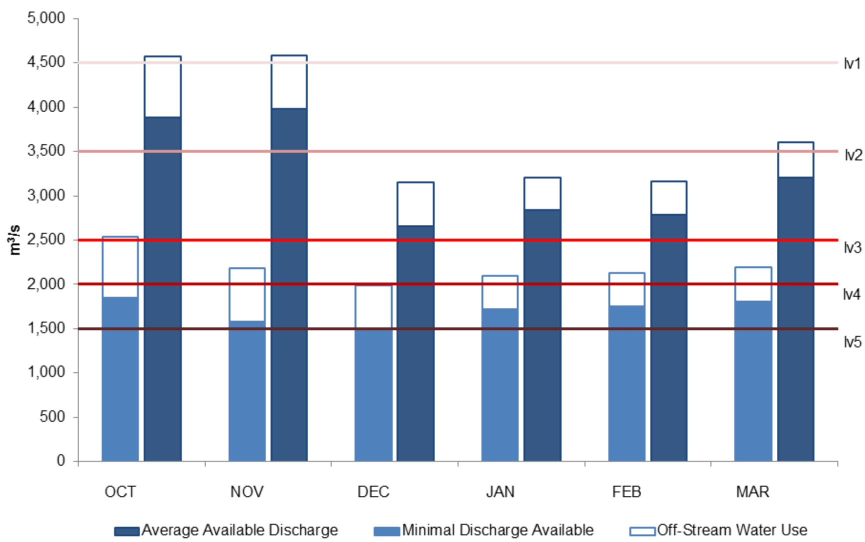

Figure 3-3. Comparing average off-stream water use with average monthly Sixianjiao Discharge (Q_{SD}) (dark blue) and minimal monthly Q_{SD} (light blue) during the study period. The overall height of the bar represents the Q_{SD} volume. Blank frames represent the water withdrawn for off-stream uses.

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.

3.3.4 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 3-4, 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.

In addition to the contribution of the Datengxia Reservoir, Figure 3-4 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 decreased water use intensity 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 decreased water use intensity 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.

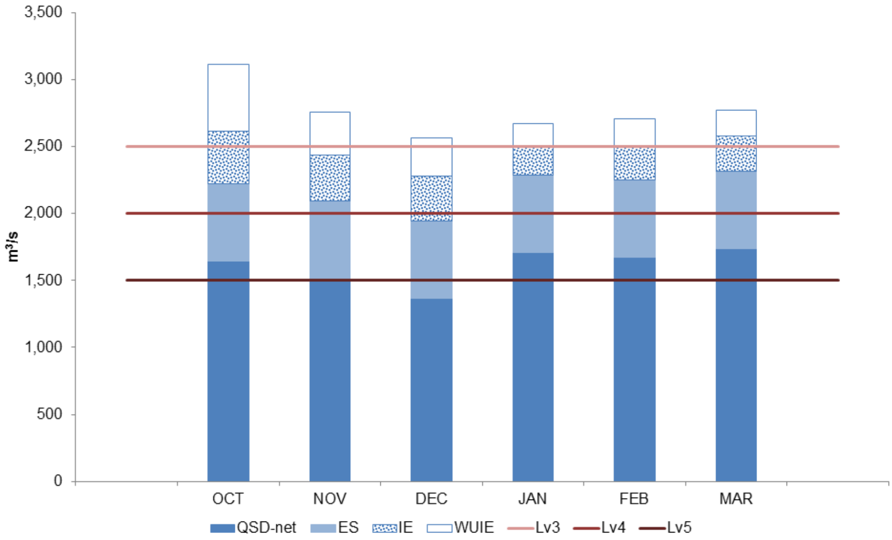

Figure 3-4. Effect of the ES and MP strategy on saving Q_{SD} for suppressing the salt intrusion in 2004-condition. The overall height of the bar represents the Q_{SD} volume. Q_{SD}-net is the "net" Q_{SD} after extraction for off-stream uses; ES is the expected minimum improvement of the Datengxia 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}-net, MP, and WUMP

3.4 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 are also part of the story (Zhang et al. 2010).

3.4.1 Uncertainty

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

Uncertainty in current strategy

I 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 Q_{SD} 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 et al. 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 3-2). 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 (He et al. 2012, Kong et al. 2010). This indicates that a larger Q_{SD} will be required to combat severe salt intrusion under future conditions.

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 held to ensure food security by allowing certain amount of cropland only for production of grains, cotton, oil crops and open-field vegetables. Whether the policy will be adjusted remains uncertain.

Next, influence of the decreased domestic water use intensity may be overestimated. Prior studies suggest domestic water use in the developed country is significantly influenced by outdoor applications like home gardening (Domene and Sauri 2006, Syme et al. 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.

I 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 intensity of Germany. Otherwise the effectiveness of the MP strategy may be altered by the different water use intensity achieved in the PRD.

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 (Pearl River Water Resources Commission 2015), 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.

3.4.2 Policy implications

Although the Datengxia hydro-engineering project is often considered as the necessity to alleviate severe salt intrusion problems (Liu et al. 2010), 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 decreasing water use intensity. 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 (Zhang et al. 2008). Constructing large reservoirs/dams in the downstream area is strongly restricted by the fast growing population, and shrinking land resources (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 3-1). 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.

3.4.3 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.

3.5 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.

4

This chapter is based on:

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Chapter 4

Building regional water-use scenarios consistent with global Shared Socioeconomic Pathways

Abstract

Water use projections are crucial to safeguard sustainable access to freshwater in the future. The Water Futures and Solution initiative (WFaS) has developed a set of global water-use scenarios consistent with the recent Assessment Report framework of the Intergovernmental Panel on Climate Change, notably the Shared Socioeconomic Pathways (SSPs), and applying a hydro-economic classification that links a socioeconomic dimension with hydrologic complexity. Here I present regional water use projections for the Pearl River Delta (PRD) in China consistent with the WFaS global assessment. Using two different downscaling techniques for developing regional water-use scenarios based on the national assumptions made for China in the WFaS assessment, I investigate PRD's water-use projections. The findings indicate significant differences in the PRD's regional development trends compared to China's national SSP. The regionalized scenarios project lower water use because of the PRD's lower share of the manufacturing sector in total Gross Domestic Product (GDP) and higher rates of technological improvement, compared to national development trend assumptions. Nevertheless, hydrological challenges remain for the PRD. Its total water use would still increase by up to 54% in 2030 under the regionalized scenarios. Although uncertainties related to scarce data remain, I provide a scientifically sound and feasible method to generate regional scenarios that can capture the regional sectorial water uses development as well as being consistent with national water-use scenarios developed by global assessment.

4.1 Introduction

Population growth and socio-economic developments have fundamentally changed the drivers of freshwater use by humans (Hoekstra and Chapagain 2007). Over the last few centuries, global human water use has been increasing exponentially as a result of growing food demand and increasing living standards (Vörösmarty et al. 2005). The growing water use is approaching total renewable freshwater availability in many regions, and as a result, freshwater is becoming one of the most limited resources (Wiek and Larson 2012). For future management, both water availability and water-use projections are required to safeguard sustainable access to freshwater to sustain livelihoods, well-being, and socio-economic development (Pahl-Wostl 2007, UN-Water 2013). The impact of socio-economic changes on water use has been assessed by several studies based on conventional global change scenarios (Alcamo et al. 2003b, Alcamo et al. 2007, Oki and Kanae 2006, Vörösmarty et al. 2000). For example, the global socio-economic scenarios of the Special Report on Emission Scenarios (Nakicenovic et al. 2000), or the continental change scenarios like the Water Scenarios for Europe and Neighbouring States (Kamari 2008). Recently, a new set of global change scenarios has been released (Moss et al. 2010). These new scenarios follow a scenario matrix architecture (O'Neill et al. 2014, van Vuuren et al. 2014). The two axes consist of : (1) the level of radiative forcing of the climate system characterised by four different Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011); and (2) a set of alternative futures of societal development, the Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2015). SSPs and RCPs were independently developed in the context of the Intergovernmental Panel on Climate Change (IPCC) Assessment Report framework (Moss et al. 2010, van Vuuren et al. 2014). Researchers have already started using these scenarios for global water-use assessment with various global hydrological models (Bijl et al. 2016, Hanasaki et al. 2013, Mouratiadou et al. 2016). A recent work was carried out by the Water Futures and Solutions initiative (WFaS; http://www.iiasa.ac.at/WFaS), which is a collaborative, stakeholder-informed effort applying systematic global scenario analysis to identify future hotspots of water insecurity. The WFaS developed a set of water-use scenarios consistent with the SSPs and RCPs, and estimated the global sectorial water use using a state-of-the-art multi-model framework (Wada et al. 2016) (The term "water use" in the WFaS assessment refers to water withdrawal. The present paper adopts this term. Note that water use does not refer to "water consumption", defined as water withdrawal minus return to the river system after usage, e.g. for cooling, irrigation).

The SSP narratives provide five qualitative descriptions (SSP1/2/3/4/5) of conceivable future changes in socio-economic development (e.g., demography, economy and lifestyles, policies and institutions, technology, environment, and natural resources), at the level of large world regions to serve as a basis for integrated scenario analysis. Among the five SSP narratives, the SSP2 world ("Middle of the road") is characterized by development similar to historical trends. The SSP1 world takes the "Green road" towards a more sustainable path, whereas the SSP3 world takes the "Rocky road," with resurgent nationalism and severe challenges for climate mitigation and adaptation. The SSP4 world follows a highly unequal path ("A road divided") with adaptation challenges dominating, while the SSP5 world follows rapid fossil-fuelled development ("Taking the highway") and mitigation challenges dominate (O'Neill et al. 2015). Although its key elements focus on climate policy analysis, the SSPs offer the possibility of extending the basic narratives into various dimensions for the analysis of broader sustainable development objectives. In the WFaS initiative, the SSP storylines have been enriched with critical water dimensions that will affect sectorial water uses. This has provided a set of water-extended SSP narratives including qualitative changes in the diverse drivers of societal water use, which were translated into a set of quantitative assumptions for implementation in the multi-model assessment (Wada et al. 2016) .

In addition, the WFaS initiative developed a hydro-economic (HE) classification for describing different conditions pertaining to water security. The HE classification links regional hydrologic complexity with the capacity of a country or region to cope with water-related risks, both of which have an impact on development and are used to differentiate scenario drivers (Fischer et al. 2015).

However, there are no studies, as yet, investigating whether these global-level scenarios and data are relevant in helping to achieve management goals for regions within countries. Van Ruijven et al. (2014) show that retaining the spatial coherence across different scales while enhancing their applicability is important to improve the usefulness of the SSP scenarios. To assess future sustainability of sectorial water use in large countries like China, understanding the behaviour of water users at the regional level is crucial. Ultimately, national and global sustainable development can only be achieved by the cumulative efforts of each individual region where practical adaptive measurements are employed. Previous research on China's Pearl

River Delta (PRD) suggests that a global assessment may be insufficient to reflect future trends of sectorial water uses on a regional scale (Yao et al. 2015). Against this background, in this paper I attempt to address water-use development at a regional level in the near future in a way that is consistent with global socio-economic scenarios. More specifically, the objective of this study is to propose a scientifically sound and feasible methodology to downscale the scenarios developed for global assessments to capture the development of sectorial water use on a regional level. Key questions include:

1. How can I develop regional water-use scenarios that are consistent with the global SSP storylines and associated national data as well as available regional data?
2. Compared with the national assumptions regarding economic and population growth for China, to what extent do regional narratives and assumptions affect the projected regional sectorial water uses?
3. If the regionalization of global scenarios leads to a different future, which socio-economic factor explains most of this difference?

I selected the PRD as study area for its unique development path in comparison with the rest of the country (Seto et al. 2002), and propose two different approaches to develop water-use scenarios at the regional level. One follows the assumptions for China from the global assessment. The other adjusts these national assumptions based on PRD's historical development trajectory and current regional development policies. Sectorial water uses under both scenario sets were projected until 2050 using a global water-use model. The analysis compares the resulting estimation of water uses and assesses the impact of regional characteristics on scenario development. By comparing the results from these two scenarios, I then can assess whether the national assumptions generated in the global assessment can capture the regional dynamics in sectorial water uses, and how to develop a regional water-use scenario consistent with global scenarios and socio-economic trends. I discuss the implications of our findings for achieving sustainable water use, the study scope and the data limitations, and finally draw conclusions.

4.2 Methodology

4.2.1 Study area

The PRD, located in Guangdong Province, southeast China (Figure 4-1), is the area surrounding the Pearl River estuary and includes nine major urban centres. By 2010, the PRD had become the largest urban area in the world with 56 million inhabitants, accounting for 4% of China's total population and generating 10% of the country's GDP. More than 80% of PRD's population lives in cities, whereas China's total urbanization rate is only 50%

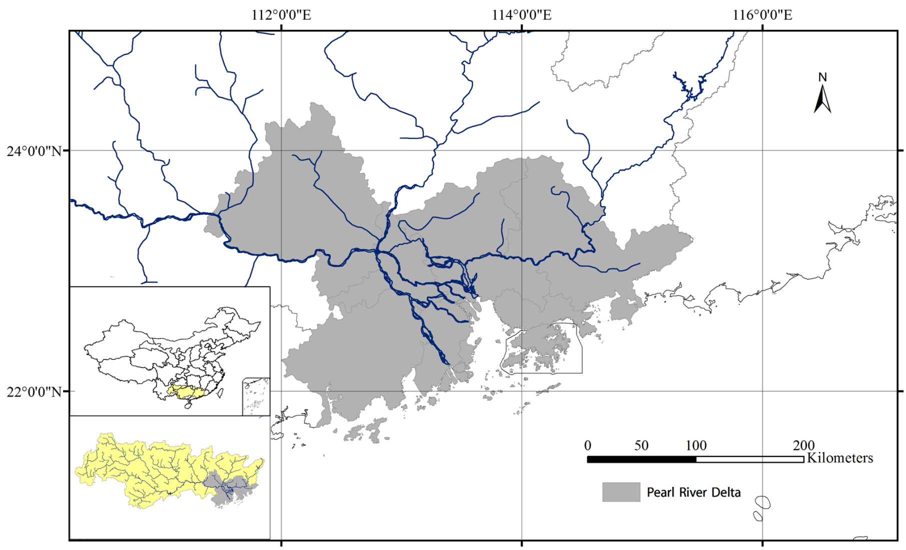


Figure 4-1. The Pearl River Delta. The bottom inset shows the location of the delta area in the whole Pearl River Basin, the one above shows the Pearl River Basin in China

The total annual water use in the PRD is about 25 billion m^3, some 4% of China's overall water use at present. In 2002, industry (comprising manufacturing and electricity generation) was responsible for 42% of the total water use in the PRD. Since then, industry has surpassed agriculture to become the dominant water user in the area. In 2010, industrial, agricultural and domestic water use accounted for 43%, 32% and 21% of the total water use respectively (Water Resources Department of Guangdong Province 2016).

The PRD is among the most water-abundant regions in China, located in the humid sub-tropical zone and receiving more than 1700 mm of water in average annual precipitation. Nevertheless, seasonal water shortages have been reported more frequently during the last decade (Tu et al. 2012). The reported water shortages are mainly caused by the severe salt intrusion in the dry season when upstream water abstraction deteriorates the salt-suppressing capacity of the low flow (Chen 2006a).

4.2.2 Water use model

In line with the WFaS initiative global assessment, the present study builds on the initial global water scenarios that were developed based on the SSPs and RCPs consistent with the IPCC Assessment Report framework. I selected WaterGAP 2.2 (Flörke et al. 2013, Muller Schmied et al. 2014), one of the global water-use models applied by the WFaS initiative, for the quantification of future pathways of domestic and manufacturing water use in the PRD. A key advantage of WaterGAP is that it disaggregates the industrial sector into water used for cooling in electricity generation and used in the manufacturing sector. In 2010, about 13% of the total water use in the PRD was for electricity generation, i.e., it accounted for more than a third of the total industrial water use. However, estimating the future dynamics of water use for electricity generation in the PRD is not feasible for the present study because of limited data availability.

WaterGAP (Flörke et al. 2013) estimates manufacturing water use according to equation:

$$MWU_t = MSWI_{2005} \times MVA_t \times TC_t$$

where MWU_t is the annual manufacturing water use in year t; $MSWI_{2005}$ is the manufacturing structural water use intensity in the base year 2005; MVA_t is the manufacturing value-added; and TC_t is the annual technological change rate for the manufacturing sector.

Estimation of domestic water use (DWU) is achieved in WaterGAP by using population numbers (POP), annual technological change rate (TC), and domestic structural water use intensity (DSWI).

$$DWU_t = DSWI_t \times POP_t \times TC_t$$

The $DSWI_t$ represents the change in domestic water-use intensity as result of changes in aspects such as habit or the number of water users. It is represented by a sigmoid curve as a function of the GPD per capita (GDPca) (Alcamo et al. 2003a).

$$DSWI = DSWI_{min} + \frac{DSWI_{max}}{1 - e^{-\gamma \cdot GDP_{ca}^2}}$$

A value of 50 L/person-day was used as $DSWI_{min}$ the minimum requirement (Gleick 1996). The maximal domestic structural water use intensity ($DSWI_{max}$) and the curve parameter (γ) are fitted to the PRD based on its reported water-use records from

2000 to 2010, following a previous study (Yao et al. 2015). The model with calibrated parameters was then validated by the newly released water-use records from 2011 to 2013. The water-use records and socio-economic data are reported by Water Resources Department of Guangdong Province (2016) and Guangdong Statistics Bureau (2016), respectively.

Agricultural water use largely depends on the investment capacity for technological transitions (Wallace 2000). Here, the reported reduction of agricultural water-use intensity (water used per hectare) was used to estimate the effects of technology on agricultural water uses. During 2000-2010, the agricultural water-use intensity of the PRD was reduced by about 2% annually from 11475 m^3/ha to 9210 m^3/h, i.e., an annual rate reduction comparable to that of the PRD's industrial water-use intensity (Water Resources Department of Guangdong Province 2016). Thus, I assume that technological transition in the agricultural sector follows a similar rate as in the manufacturing sector.

$$AWU_t = AWU_{2010} \times TC_t$$

where AWU_t is the future agricultural water use, and AWU_{2010} is agricultural water use in base year 2010. Data were collected from Guangdong Water Resources Bulletin (Water Resources Department of Guangdong Province 2016). TC is the annual technological change rate.

4.2.3 Building scenarios for the Pearl River Delta

The present study generated two scenarios sets for the PRD following the SSP framework, namely SSP-CN and SSP-PRD. Each scenario set contains five scenarios following the original SSPs (SSP1-5). Within each scenario, I investigated four socio-economic dimensions to project the future sectorial water use, i.e., economic development (GDP), population growth, structural GDP changes determined by the share of the manufacturing value-added in the total GDP, and the annual technological change rate.

Socio-economic development

The first set of scenarios (SSP-CN) follows the national assumptions for China used in the WFaS initiative for the period 2010 to 2050, thereby reflecting homogenous development in the future across the entire country. The PRD is thus assumed to exhibit the same GDP growth rate and the same contribution of manufacturing to the total GDP as the rest of the country. Today 4.19% of China's population lives in the PRD, a share assumed to remain constant over time. Quantitative assumptions for China's population and GDP growth were compiled from the SSPs database[7], the IIASA-VIC v9 and OECD Env-Growth v9, respectively. Changes in manufacturing value-added were derived from the UNEP GEO4 Driver Scenarios[8] (Rothman et al. 2007).

In reality, however, a region's development trajectory may well be very different compared to the average national development of the country. For instance, a region can benefit from other regions by maximizing the effectiveness of resource utilization and economic development. As China's "youngest" economic engine, the PRD has experienced a unique development path (Seto et al. 2002). To reflect this, the second set of scenarios (SSP-PRD) was constructed within the context of China's overall development, but adjusted the national assumptions from the global WFaS scenarios by taking the regional specified historic trajectories and planning targets into account.

To do this, I first scrutinized available regional projections and development plans. The Pearl River Delta Reform and Development Planning Guideline provides several detailed development targets for the PRD towards 2020[9]. According to this plan, by 2020, more than 60 million people are expected to live in the PRD. Per capita GDP in the PRD will reach the level of 30000 $US\$_{2005}$[10], and services will contribute 60% of the total GDP.

These identified planning targets were used as indicators to adjust the "Middle of the road" SSP2-CN scenario into SSP2-PRD scenario. More specifically:

1. The population under SSP2-PRD is assumed to reach 60 million by 2020 following the current plan. But, as the planned target is limited to 2020, it is difficult to extend the work to the longer-term SSP storyline. Thus, I assume that SSP2-PRD will have the same population growth rate as SSP2-CN during the period of 2020-2050.
2. During the past few decades, the PRD has experienced economic growth that is unprecedented in China, far above the rest of the country. By 2010, the PRD

[7] www.iiasa.ac.at/web/home/research/researchPrograms/Energy/SSP_Scenario_Database.html

[8] distributed by International Futures version 5 at pardee.du.edu

[9] Pearl River Delta Region Reform and Development Planning Guideline, published by the National Development and Reform Commission in 2008

[10] in PPP terms using constant 2005 US dollars

contributed 9.23% of China's total GDP. However, convergence of the country's economy is expected due to the more liberalized and open policy under China's "regionally decentralized authoritarian" development regime (Kanbur and Zhang 2005, Xu 2011). As a result, PRD share in national GDP will decline because the rest of China will catch up. Thus, in SSP2-PRD, the PRD's share of GDP in China was adjusted to decrease by 0.25% every 10 years so that the delta can still meet its target by 2020, which is the GDP per capita of 30,000 $US\$_{2005}$ proposed in the Pearl River Delta Reform and Development Planning Guideline.

3. In SSP2-PRD, the share of manufacturing gross value-added in total GDP was assumed to follow the historic trend, i.e., decreasing from 47% in 2010 to 42% in 2020 and further to 28% in 2050.

Next, for the remaining SSP-PRD scenarios (SSP1/3/4/5-PRD), I assume that the PRD will follow a similar development trajectory as in other economies with a comparable socio-economic status. I used PRD's GDP per capita of the base year 2010, around 15,000 $US\$_{2005}$ per person, and 10% bandwidth as the indicator to select representative economies in the present world based on World Bank national account data[11]. GDP per capita is a suitable indicator here because: (1) it reflects both total GDP growth and population growth; and (2) it better represents the average level of wealth of a region than the total GDP. In total, nine countries, namely Lithuania, Latvia, Romania, Croatia, Uruguay, Chile, Cuba, Iran, and Kazakhstan, had a GDP per capita in 2010 at the same level as the PRD (i.e., 15,000 ±10% $US\$_{2005}$). For each of these countries, the national projections of GDP and population under SSP1/3/4/5 were calculated as percentage differences in comparison with the respective SSP2 projection. The average differences across all countries were then applied to SSP2-PRD to quantify GDP development of the SSP1/3/4/5-PRD.

Technological improvement

All three sectorial water uses, agriculture, domestic and manufacturing are affected by the TC, leading to improvements in water-use efficiency (i.e., output per unit of water), and thereby decreasing water-use intensity (i.e., water use per unit of output in the respective sector). TC estimation is consistent with the WFaS approach, which quantifies annual technological improvement rates for each of the

[11] data.worldbank.org

combinations of SSPs and HE classifications using a range of historical observations (Wada et al. 2016) .

The HE classification assigns a country or region to a two-dimensional hydro-economic space. In contrast to the scenario space of SSPs, which is defined primarily by the nature of the outcomes, the two dimensions of the HE space are defined based on inputs or elements that led to the outcomes, e.g., GPD per capita and hydrological conditions like total renewable water resource per capita. The Y-dimension proxies the economic and institutional capacity of a country or region to cope with water challenges and the X-dimension reflects the magnitude and complexity of challenges regarding the management of available water resources. For water scenario development, the HE space is divided into four quadrants, each includes countries characterized by a different level of economic capacity and hydrological challenges (Fischer et al. 2015).

To assign a country or region its HE spaces, two normalized compound indicators are calculated from a number of component indicators. GDP per capita is used as proxy for economic-institutional coping capacity, whereas the hydrological complexity includes four component indicators: (1) total renewable water resources per capita; (2) intensity of water use as ratio of water withdrawal to total renewable water resources; (3) monthly runoff variability; and (4) the dependency of external water resources by measuring the share of external to total renewable water resources.

Details of computing these compound indicators and quantifying the TC in combination with the SSPs storylines can be found in Fischer et al. (2015) and Tramberend et al. (2015). For the present study, TC assumptions for China in the WFaS analysis were deployed in SSP-CN. For the SSP-PRD scenarios, I estimated a region-specified TC for the PRD based on its socio-economic and hydrological conditions by using the HE classification. The same TC is used across all three sectors under each scenario set. Table F1-F4 in the Appendix F provide a more detailed overview of the quantitative scenario assumptions.

Future water security

Over time, countries or regions shift in the two-dimensional space of the HE classification as a result of changing conditions in socio-economic coping capacity (Y-axes) and impacts of climate change on hydrological complexity (X-axes). In the analysis, I explored the trajectory of the location of the PRD in the HE classification, which represented the changing future conditions with respect to water security.

The PRD's future HE classification was simulated using: (1) socio-economic and water-use data projected by SSP-PRD; and (2) hydrological conditions (Pearl River discharge and local runoff) simulated by the Variable Infiltration Capacity Model (better known as VIC) for the Pearl River Basin on a 0.5 x 0.5 decimal degrees resolution using five Global Climate Models outputs on a daily basis for the period of 2010-2100 under the IPCC scenario RCP4.5 (moderate climate change scenarios) and RCP8.5 (most severe climate change scenarios) (Yan et al. 2015).

The minimal discharge from a graded salt intrusion warning system for the PRD was considered to be the basic environmental flow requirement (Wen and Yang 2006). Surplus discharge from all three tributaries of the Pearl River above this level was considered to be the external renewable water resource for the PRD. The gridded runoff data from the PRD area represented the internal renewable water resources.

Finally, I explored which variable contributed the most to the difference of sectorial water uses between SSP-CN and SSP-PRD. This was achieved using a multiple linear regression and subsequent plotting of model residuals against fitted values (Zuur et al. 2009). Both analyses was conducted in R (R Core Team 2013).

4.3 Results

The results focus on the comparison between the two scenario sets in terms of the characteristic behaviour of sectorial water users under the various scenario assumptions described above. In addition, I explored the potential development of PRD's water security as represented by its HE classification. Please note that hereafter, the term "SSP scenarios" refers to the SSP-CN and SSP-PRD scenarios developed for the present study, rather than the original SSP scenario descriptions (O'Neill et al. 2015).

4.3.1 Linking global and regional scale

The two scenario families SSP-CN and SSP-PRD illustrate two different downscaling techniques to link the national assumptions for China—developed and applied in the global assessment—with the regional scale of the PRD. Table 4-1 summarizes the development of socio-economic variables for each of the two scenario sets. By 2050, the PRD is projected to have a larger economy under SSP-CN than under SSP-PRD, with up to 34% difference in total GDP (SSP1). At the same time, the dependency of GDP growth on the manufacturing sector is projected to increase under SSP-CN, but decrease under SSP-PRD, resulting in a difference between the two of up to 86% (SSP3). The disagreement between the two scenario sets is caused by the fact that SSP-PRD incorporates regional characteristics into the national assumptions from the global assessment, whereas SSP-CN deploys the national assumptions directly on the regional level. By incorporating the regional characteristics, the socio-economic development projected under SSP-PRD fits better to PRD's historical trend, for example, the share of manufacturing value-added in GDP.

Moreover, as can be seen from Figure 4-2, the projection of PRD's potential GDP growth under SSP-PRD is well covered by SSP-CN, especially for the near future. However, the contribution of the manufacturing sector to the total GDP differs strongly between the two sets of scenarios, indicating that the national assumption from the global assessment can capture the overall economic development on a regional level well, but fails to capture the sectorial details, which may lead to significantly different projections for future of water use.

Table 4-1. Socio-economic development in the PRD under two scenario sets

	SSP-CN					SSP-PRD				
	SSP1	**SSP2**	**SSP3**	**SSP4**	**SSP5**	**SSP1**	**SSP2**	**SSP3**	**SSP4**	**SSP5**
GDP,PPP (billion constant 2005 US$)										
2010	856	856	856	856	856	843	843	843	843	843
2030	3,350	3,076	2,932	3,059	3,624	3,012	2,932	2,825	2,892	3,272
2050	6,180	4,719	3,718	4,699	7,509	4,605	4,194	3,638	4,143	5,953
Population (million people)										
2010	56.2	56.2	56.2	56.2	56.2	56.0	56.0	56.0	56.0	56.0
2030	56.9	57.8	58.6	56.5	56.9	58.6	60.1	61.8	58.8	58.5
2050	51.3	52.9	54.8	49.6	51.3	52.0	54.9	59.0	51.5	52.0
Share of manufacturing value added in GDP (%)										
2010	42.6	42.6	42.0	42.6	42.6	47.5	47.5	47.5	47.5	47.5
2030	49.2	49.4	46.3	49.2	49.4	39.2	38.1	36.7	37.6	42.5
2050	48.9	49.2	46.5	48.9	49.2	31.6	28.8	25.0	28.4	40.9

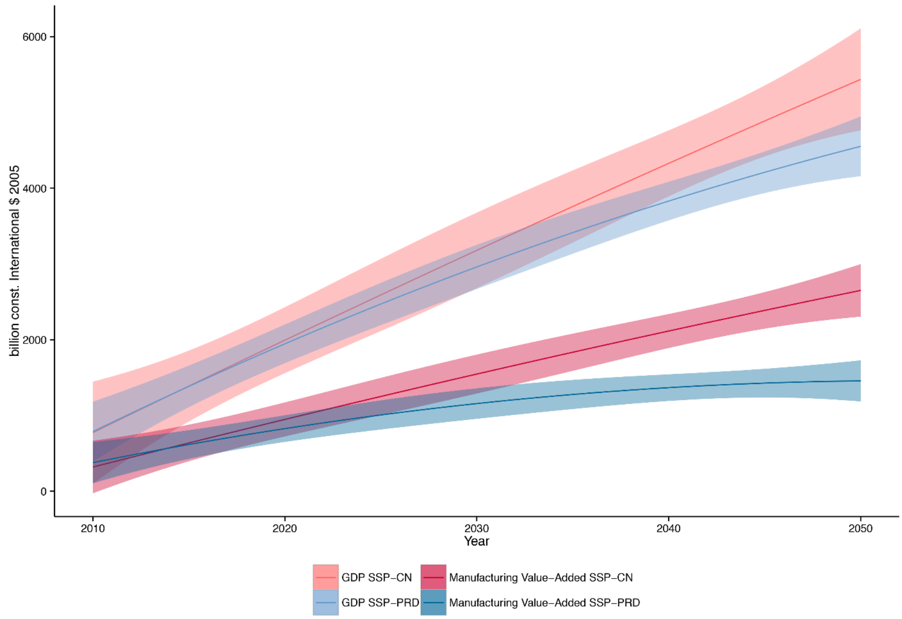


Figure 4-2 Comparison of GDP and manufacturing value-added projection under SSP-CN and SSP-PRD

4.3.2 Future water use

Figure 4-3 presents the different trends of future water use projected under the two scenario sets. PRD's annual water use doubles from 21 billion m^3 in 2010 to up to 50 billion m^3 by 2050 under SSP-CN, but only increases by 14% on average under SSP-PRD. Under SSP5 the PRD experiences the most water use, which increases by 132% (SSP-CN) and 57% (SSP-PRD). SSP-CN scenarios highlight a steep increase of total water use in all five paths, whereas the total water use under SSP-PRD peaks around 2030, then curves in SSP1/2/3/4. SSP5-PRD is an exception, which only manages to stabilize the total water use after 2040. By 2050, SSP5-CN projects the largest net increase of water use among all the scenarios, whereas SSP3-PRD expects a 5% decrease in total water use.

The dynamics of future water use are largely driven by the manufacturing sector, the only sector where water use increases by 2050 resulting from the increasing GDP. On average, more than 60% of estimated total water use in 2050 is attributed to the manufacturing sector. SSP5 projects the largest contribution of 81% (SSP-CN) and 74% (SSP-PRD).

Water use in all three sectors is affected by different rates of technological improvement under the two sets of scenarios, because of different HE classifications.

By 2050, domestic water use will decrease by 30% (SSP-CN) and 38% (SSP-PRD) because of the joint effect of technological improvement and a curved population growth. Agricultural water use in this study is affected only by technological improvement, and decreases by 25% (SSP-CN) and 36% (SSP-PRD).

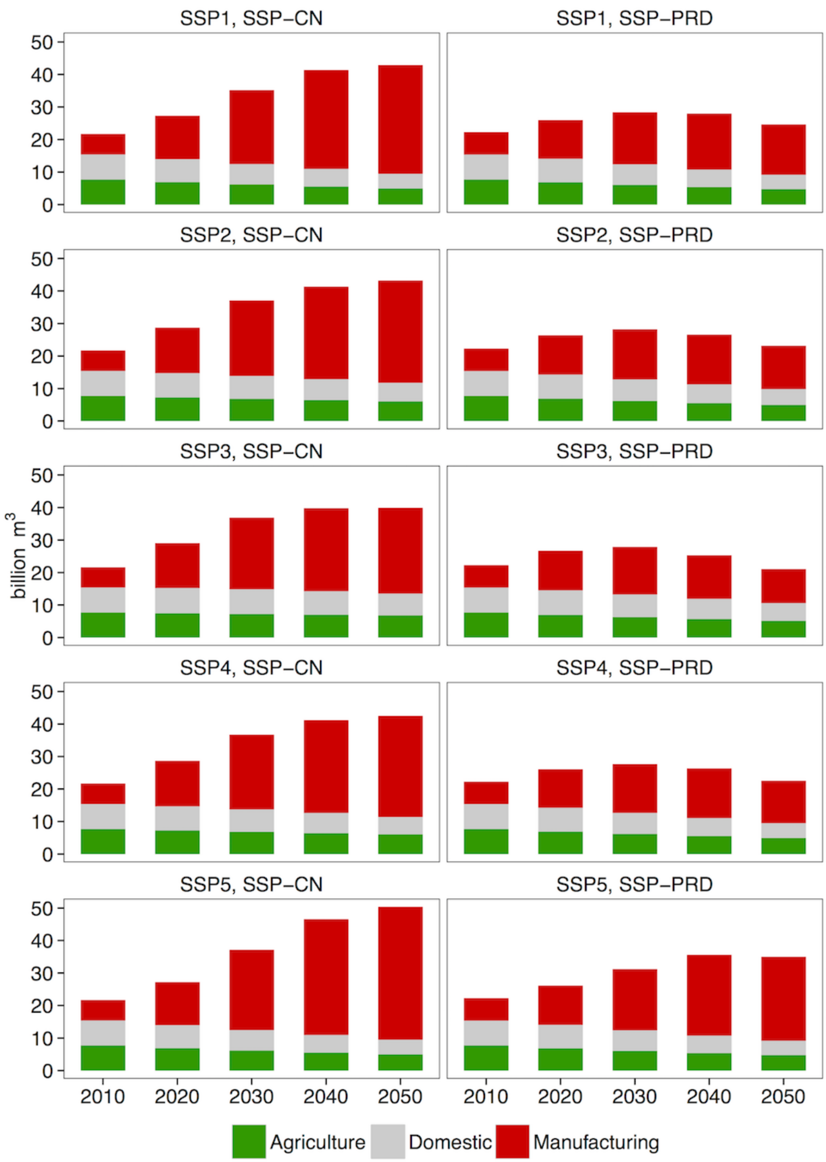


Figure 4-3 Sectorial water use projection under different scenarios. The SSP-CN scenario set follows the national assumption for China used in WFaS, the SSP-PRD set contains PRD-specified regional scenarios

4.3.3 Water security in future

Figure 4-4 shows the trajectory of the PRD's HE classification in the coming few decades under different SSPs (economic growth) and climate change scenarios (changing hydrological conditions), in comparison to the current status of China and other selected countries.

The PRD will most likely face increased hydrological challenges even under the most sustainable pathway included in the study, the combination of SSP1 with RCP4.5 scenarios. If the world follows the RCP8.5 scenario and the delta decides to further develop its large economy following SSP5, hydrological conditions in the PRD become more challenging and unstable (see the wiggle curve in Figure 4). At the same time, the PRD's economic capacity to cope with the potential challenges of hydrological complexity increases rapidly (Figure 4-4). This may indicate that despite the increasing hydrological complexity, the PRD is likely to have enough economic capacity to meet the challenges, provided the economic strength gained over time (as expressed in the proxy variable GDP per capita) is used for efficient management of increasing hydrological challenges and institutional capacity is in place to cope with these challenges.

4.3.4 Sensitivity of variables on water use

The four socio-economic variables used in the present study, GDP, population (POP), share of manufacturing value-added in GDP (MAN) and technological change rate (TC) are investigated using a multiple linear regression to identify the factor most responsible for the large differences in water use under the two scenarios sets (Table F5 in Appendix F). In general, for all the five SSPs, differences in the TC contributed the most to the sectorial water use differences between SSP-CN and SSP-PRD. The reason for this may be twofold: (1) TC affects all three sectorial water uses; and (2) the TC of SSP-PRD is faster compared to that of SSP-CN, which follows the assumption of the HE classification from the global analysis. Although less influential than overall GDP growth, differences in MAN also contributed. Although POP is one of the main drivers for the total water use, the different population assumptions under the two scenario sets do not lead to significant different total water use by 2050.

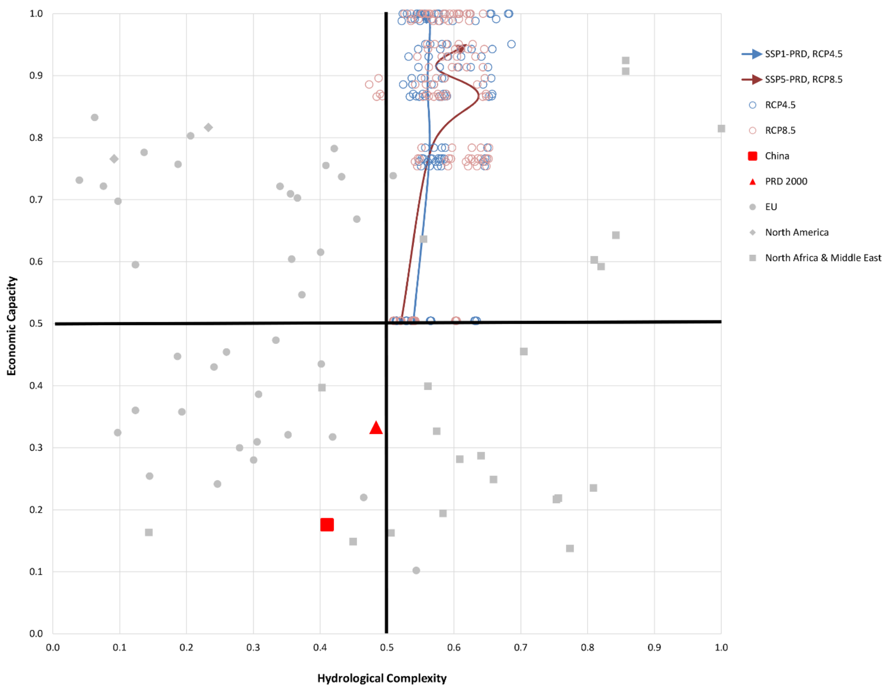


Figure 4-4. HE classification of the PRD under different scenarios compared to China and other countries. Blue and red circles are the PRD's HE classification for different SSPs and RCPs projections, from 2010 to 2050 with time steps of 10 years. HE classification for China (red square), PRD (red triangle) and other countries selected (grey shapes) are for the year 2000

4.4 Discussion

4.4.1 Developing globally consistent regional scenarios

Our results indicate that when the development trends of a scenario for China derived from the global assessment are directly applied to the PRD (scenario group SSP-CN), future total water use in the PRD tends to be overestimated, because of regional deviations from the overall development in China (Figure 4-3). This suggests that incorporating additional location-specific characteristics is an important step in developing regional scenarios from global information. It is thus of particular importance to develop an informed link between regional projections and the global assessment in the process of downscaling the regional scenarios from national assumptions. In this study, this was achieved by first scrutinizing existing development plans for the PRD and incorporating key features in the scenario group SSP-PRD. The scenario "Middle of the road" SSP2-PRD was first scaled following those plans and the four other SSPs were then downscaled applying the same relative relation to SSP2 as the global scenarios. A key strength of this approach is that it is particularly suitable for regions where only a business-as-usual scenario exists.

SSP-CN projects a far larger net increase in water use for manufacturing than SSP-PRD does. This is the result of China's continuously expanding manufacturing sector under all the SSP-CN scenarios, as projected in the global assessment for all emerging economies across the world (Table 4-1). However, the PRD today is among the most urbanized and industrialized regions in the country. During the last decade, the economic structure has been steadily transforming from industry to services. Thus, following the historic trend, the share of manufacturing value-added in total GDP decreased for all SSP-PRD scenarios.

In addition, the PRD has a very different technological improvement path compared to China (Yao et al. 2015). Being allocated in the right-upper corner of the HE classification I employ here, the PRD has a better economic and institutional starting position for technological improvement compared to many other regions in China. Moreover, the high challenges of the PRD's complex hydrological conditions urge for an implementation of water-saving technologies. The technological improvement in SSP-PRD is thus expected to be significantly faster compared to SSP-CN, especially under SSP3, where the technological improvement rate is three times faster in SSP3-PRD than in SSP3-CN.

Through a shift of the GDP growth from manufacturing to services, combined with a more rapid implementation of technological improvement resulting in higher water use efficiencies, by 2050 the PRD can cut its total water use by 56% on average in SSP-PRD compared to SSP-CN. Thus, regionalization based on regional characteristics is crucial in projecting future socio-economic growth and its impact on future water use on a regional level with global data and information. These results support a previous study by (Yao et al. 2015), which concludes that the existing global assessments may generate water use pathways different from the actual development in specific regions of developing countries.

Nevertheless, the PRD is unique in China as the economic development zone attracts enormous investment and policy-support since the beginning of the reform and opening up. Thus, the remarkable difference found between SSP-PRD and SSP-CN may not be seen in the rest of China. That is, if a region's development differs from the PRD but is close to the average national development, SSP-CN may be well able to project the region's future development without need for regionalization.

Building up regional scenarios through a bottom-up procedure following the SSP context may be an alternative way to "downscale" the SSP narratives to the regional level. Such a bottom-up procedure could allow more freedom to incorporate greater numbers of regional specified variables, possibly resulting in more plausible development projections for that region. Our attempt of applying this bottom-up approach is transferable, especially to those regions with past development paths that differ from their country's. However, it also requires more extensive regional-scale datasets, and preferably a clear long-term development planning target. More participatory efforts from stakeholders and regional experts are also needed to fit the scenarios into the SSPs context, while the improvement to the output remains uncertain.

4.4.2 Study limitations

Although the bottom-up procedure could generate more regional specified scenarios to better capture future development, it also requires sufficient regional specified variables and data to support the analysis. An important aspect to incorporate, but lacking in our study, is a long-term planning target for socio-economic growth in the PRD for the future beyond 2020. Consequently, the ability to capture the regional specified development may be compromised for the long-term projection. For instance, in our study the population in the SSP-PRD after 2020 has the same growth rate as SSP-CN.

The present study is also limited with respect to the sectors it considers. Data limitations for the thermo-electricity sector make it very difficult to associate this sector with the SSP storylines in a consistent way. To assess the future water use in the electricity-generation sector, the key information required include number, type and installed capacity of thermal power plants and, the type of cooling system used. However, none of these are sufficiently available for the study area.

Manufacturing water-use intensity heavily depends on the structural composition of this sector and the corresponding technology it adopts. However, no sub-sector water-use data is available. Thus, sub-sectorial changes within the manufacturing sector cannot be implemented in either this study or in the WFaS global assessment. Moreover, the current results are based on the assumption that future water use will not be limited, i.e., the results would be different if sectorial water use responds to competition over limited water resources. Manufacturing water use, for example, may be limited because available water will first be allocated to domestic water use and food production. This may force the manufacturing sector to improve the water use intensity even under the SSP-CN scenarios. Thus, the current assumption may overstate the difference between the two scenarios.

This study would also benefit from additional analysis of the agricultural sector. The reasons behind the reported improvement in the agricultural water-use intensity are not specified in the report. It may be a mixed effect of changes in technology and climatic conditions. The present study can hardly separate the effects as a result of limited data availability. I can only assess possible improvements from technological changes. Land-use change may also affect agricultural water-use intensity, because of changes in the agricultural production system. For example, replacing open-field vegetable production with highly efficient greenhouses may improve the water use intensity. However, the Integrated Assessment Models for SSPs scenarios have not yet published results for land-use change that include irrigated areas and livestock production systems at the time of this analysis. Although our result shows a decreasing trend of total agricultural water use (Figure 3), it should be emphasized that this can only be achieved if the water-use intensity in the food production system follows the suggested technological improvement, for example by promoting water-saving irrigation systems. Assessing the impact of future water use from land-use changes is beyond the scope of the present study. However, historic trends reveal a 30% decline of cultivated land in the PRD from 8460 km^2 in 1996 to 5900 km^2 in 2007 (Ye et al. 2013). Continuation of this trend will certainly affect the agricultural water use.

Exploring the potential trajectory of the PRD in the HE classification and comparing it to the present world, suggests that after 2030s the PRD will surpass the current economic capacities of countries to invest in and adopt state-of-the-art water saving technologies. I realize that GDP per capita, the vertical axis of the HE plot, is a fairly limited indicator of a country's capacity to adapt to water challenges. More comprehensive methods to assess this adaptive capacity exist, for example, the adaptive capacity wheel (Gupta et al. 2010). Though a full analysis using this framework or inclusion of additional potential indicators (e.g., the corruption perception index, Human Development Index or level of education) is beyond the scope of the present analysis, I believe China, and perhaps even more so the PRD, would score rather high on many of its criteria. However, whether the PRD can maintain the suggested fast technological improvement remains uncertain. Lack of incentive to import or invest in new technologies may hamper the PRD's technological advance, especially when other development goals are prioritized over sustainable water management. Moreover, the PRD will face the increasing hydrological challenges caused by climate change, regardless of the potential economic capacities the region can achieve.

Assessing regional water use with global scenarios or data establishes a linkage between regional development and the external environment. Assessing the balance of future water use and the availability of renewable water resources on the regional level needs to be considered for the estimation of realistic growth rates of future water use. These will, in turn, support and help facilitate sustainable water resource management. To further improve the robustness of regional water-use projections consistent with the global assessment, important issues that need to be considered include: (1) refining regionalization of the scenarios narratives and assumptions through a participatory process with regional experts and stakeholders; (2) disaggregating the industrial sector into thermal electricity and sub-manufacturing sectors; and (3) including agricultural land-use change and production-system development.

4.5 Conclusion

Scenario analysis provides a sound basis for analysing plausible future developments. Linking scenarios across geographical scales is desirable, because it allows dynamics to be analysed together at different scales. Regional assessments benefit from such linkage in various ways, for example, using global information maintains a scientific credible global context, while providing boundary conditions of the external development environment (Zurek and Henrichs 2007). But, before using the global scenarios on regional level, a downscaling procedure must be followed.

Being a heavily urbanized and industrialized delta area, future water use of the PRD is mostly determined by its economic growth and scale of manufacturing sector. The national assumptions and regionalized water scenarios project the similar overall GDP growth trends, but show large differences in capturing the sectorial dynamics of regional economy, which leads to large differences in water use projections. The regionalized scenarios project a lower water use because, in comparison with national assumptions, the PRD has lower share of the manufacturing sector in total GDP, and higher technological improvement rate.

Nevertheless, hydrological challenges remain for the PRD. Its total water use would still increase by up to 54% in 2030 under the regionalized scenarios.

The present study provides a scientifically sound and feasible method to derive the input assumptions for regional scenario analysis by linking regional specified historical trends and future development targets with national SSPs scenarios. Using these assumptions, I can generate the regional water scenarios that can capture the regional dynamics in sectorial water uses as well as be consistent with global scenarios and socio-economic trends. Our approach is transferable, especially to those regions that have had different development paths to their country, and preferably have accurate regional specified data regarding socio-economic development and sectorial water uses, and with clear long-term development planning target for future. Our results can be applied to help assess future sustainability of water use at regional levels consistent with state-of-the-art global assessments.

5

This chapter has been submitted to the journal Water Resources Management under the title:

Identifying and Assessing Robust Water Allocation Plans for Deltas under Climate Change

Chapter 5

Exploring future water shortage for large river basins under different water allocation strategies

Abstract

Climate change and socio-economic development increase variations in water availability and demands for water resources in the Pearl River Basin (PRB), China respectively. This can potentially result in conflicts over fresh water resources between different water users, and cause water shortage in the dry season. To assess and manage water shortage in the PRB, I developed three water use scenarios, and projected future sectorial water use under these scenarios. Then, the projected water use was confronted with future water availability under two water availability scenarios. Next, four different strategies to allocate water were defined. These water allocation strategies prioritized upstream water use, Pearl River Delta water use, irrigation water use, and manufacturing water use, respectively. The impact of the four strategies on water use and related economic output was assessed under different water availability and water use scenarios. Results show that almost all the regions in the PRB are likely to face water shortage under the four strategies. The increasing water demand contributes twice as much as the decreasing water availability to water shortage. All four water allocation strategies are insufficient to solve the water scarcity in the PRB. The economic losses differ greatly under the four water allocation strategies. Prioritizing the delta region or manufacturing production would result in lower economic losses than the other two strategies. However, all of them are rather extreme strategies. Development of water resources management strategies requires a compromise between different water users.

5.1 Introduction

As a fundamental resource, water is essential for human survival and all water users (Oki and Kanae 2006). However, fresh water resources are unevenly distributed in both time and space, which causes serious water shortage in many parts of the world (Piao et al. 2010, Yang et al. 2008). In addition, population growth and socio-economic development have exponentially increased global water use during the last few centuries. This intensified the competition over the fresh water resources between different regions and sectors (Dong et al. 2016, Liu et al. 2017, Vörösmarty et al. 2000). Solutions to water stress problems depend not only on water availability, but also on processes through which water is managed and allocated to different users or sectors (Biswas 2004). However, water resources management and allocation are facing major challenges due to increased variations in water availability caused by climate change and increased water demand because of socio-economic development (Alcamo et al. 2007).

The Pearl River is the second largest river in terms of streamflow and the third largest river in terms of drainage basin area in China (Figure 5-1). It mainly flows through Yunnan, Guizhou, Guangxi, and Guangdong provinces, and enters the South China Sea through the Pearl River Delta in Guangdong province (Zhang et al. 2007). The Pearl River Basin (PRB) is situated in a subtropical monsoon climate zone. About 80% of the streamflow occurs during the wet season between April and September (Zhang et al. 2012). Highly uneven spatial and temporal distribution of streamflow has caused seasonal water shortages in the basin (Zhang et al. 2009a). Previous study showed that rainfall and discharge during the dry season is likely to reduce because of climate change (Yan et al. 2015). Without any interventions, reduced future low flows may further aggravate seasonal water shortages in the PRB.

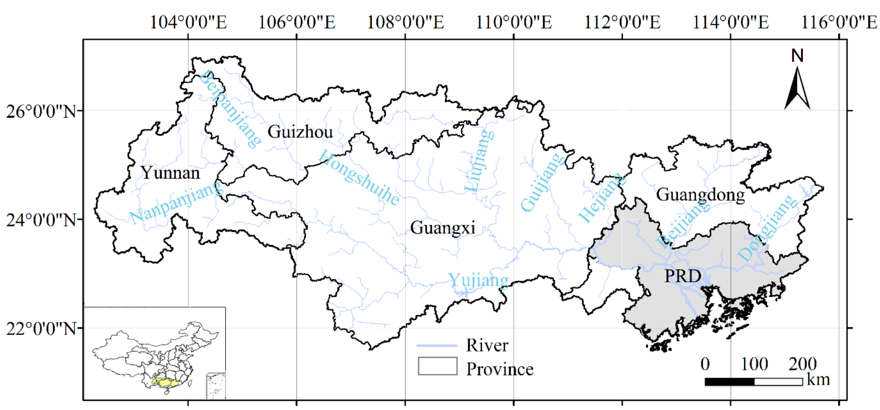


Figure 5-1. Location of the Pearl River Basin. The PRB mainly covers 4 provinces (Yunnan, Guizhou, Guangxi, Guangdong) in south China. The Pearl River Delta (PRD), which is located in Guangdong province, is the largest

urban complex in the world consists 11 important cities, include Hong Kong and Macau (Hong Kong and Macau are not include in the present study)

Socio-economic development and water consumption differ greatly across the regions in the PRB. The Pearl River Delta (PRD) accounts for 12% of the total area of the PRB and is the world's largest urban region in both population and area (World Bank 2015). It is also one of the leading economic regions and a major manufacturing centre in China (Liu et al. 2010). In 2000, the PRD used 21.3 billion m^3 water, accounting for 25.3% of the total water use of the PRB. The upstream basin, however, consists of the poorest regions in China (Jalan and Ravallion 2000). Guizhou, for instance, is the poorest province in China. Guizhou (the part within the PRB that uses water from Pearl River tributaries) is 50% larger in area than the PRD, but only used 12% of the PRD's total water use in 2000 due to the limited socio-economic activities (Pearl River Water Resources Commission 2015).

However, the poorer upstream regions are starting to catch up with the economic development in the delta since the Chinese government launched the "Western Development Program" in 1999. The program aims to boost the socio-economic development in western China including three provinces in the PRB, Yunnan, Guizhou, and Guangxi. The western development program substantially accelerated the economic growth of these three provinces resulting in increasing industrial and domestic water use in the upstream regions (Pearl River Water Resources Commission 2015). This has resulted in reducing streamflow in the Pearl River, and reduced water supply to the delta (Zheng et al. 2016). On the other hand, water use in the delta is likely to gradually increase in the near future (Yao et al. 2017), while the upstream parts of the PRB would require more water for its future development. This could result in water use conflicts between upstream and downstream regions.

In addition, saltwater intrusion is likely to further aggravate water conflicts between upstream and downstream regions. In recent years, saltwater intrusion has become a major problem in the delta. Duration of intrusion episodes is getting longer, the affected area is getting larger, and the intensity is increasing (Yan et al. 2016, Zhang et al. 2010). To reduce saltwater intrusion, the Chinese government has launched a policy named "Key Reservoirs Operational Project for Pearl River Basin" to reduce saltwater intrusion by releasing additional water from selected upstream reservoirs (He 2007, Xie 2007). The implementation of this policy reduced salt intrusion to some extent, but requires large amounts of fresh water from upstream, where water resources are already insufficient in some regions (Cai et al. 2011). Further implementation of this policy means less water to be allocated in the upstream region, thus may exacerbate the already existing water scarcity in the upstream part of the basin.

Competition for water not only exists between upstream and downstream regions, but also exists between different water use sectors. Irrigation water use accounted for 57% of total water consumption in 2000, but only 46% in 2014 (Pearl River Water Resources Commission 2015). Meanwhile, the industrial water use increased by 3 billion m^3 (from 18% in 2000 to 22.7% in 2014).

Although it is clear that competition for water will increase in the future, but the extent of the problems, the economic impacts and possible strategies to reduce competition are still unclear. To address this knowledge gap, this chapter aims to answer three research questions:

- How severe are water shortages during the dry season in the PRB under future climate change and socio-economic development?
- How do the water shortages affect economic development in the PRB?
- Can water allocation strategies alleviate competition over limited water resource in the PRB?

To answer these questions, I developed future water use scenarios using the Shared Socio-economic Pathways (SSPs) framework (O'Neill et al. 2015). Future water availability scenarios, consistent with the Representative Concentration Pathways (RCPs) (Moss et al. 2010, van Vuuren et al. 2011) are adopted from the previous study of my co-first author (Yan et al. 2015). These scenarios are used to assess the impact of different water allocation strategies on future water shortage in the dry season.

5.2 Methodology

The methodology of this study builds on the previous chapters (Yao et al. 2017, Yao et al. 2016), and studies from Yan et al. (2015) and Yan et al. (2017). The methodology consists of building water availability and water use scenarios, and developing water allocation strategies for the PRB. The scenarios are developed following a scenario matrix architecture, consisting of: 1) the level of radiative forcing of the climate system characterised by different Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011); and 2) a set of underline alternative futures of societal development, the Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2015). SSPs and RCPs were independently developed in the context of the Intergovernmental Panel on Climate Change (IPCC) fifth Assessment Report framework (O'Neill et al. 2014, van Vuuren et al. 2014).

5.2.1 Water availability scenarios

Future water availability scenarios are adopted from Yan et al. (2015). The scenarios are generated using the variable infiltration capacity (VIC) hydrological model in combination with five different global climate models (GCMs) under different RCPs (4.5 and 8.5). The VIC model is a semi-distributed macro-scale model, which is characterized by heterogeneous vegetation and multiple soil layers with non-linear base flow and variable infiltration (Hamman et al. 2016, Liang et al. 1994). The five GCMs used in this study are CNRM-CM5, EC-EARTH, HadGEM2-ES, IPSL-CM5A-LR, and MPI-ESM-LR. These five GCMs can well represent future climate change in the PRB (Wang and Chen 2014, Yan et al. 2015). See Yan et al. (2015) for details on the hydrological modelling and the development of the future water availability scenarios.

5.2.2 Water use scenarios

Socio-economic scenarios

To project future water use in the PRB, I developed a set of regional water use scenarios consistent with the SSPs was developed. The SSPs describe a set of plausible alternative trends in the evolution of society and natural systems over the 21st century, in the absence of climate change or climate policies (O'Neill et al. 2014). Three SSPs scenarios (SSP1, 2, and 3) are used in this study. SSP1 depicts a sustainable world in which the challenges for mitigation and adaptation are both low. This world is characterized by rapid technology, high environmental awareness, low energy demand, medium-high economic growth and low population. SSP3 represents a world where it is difficult to mitigate and adapt to climate change because of slow technology development, extreme poverty, and a very high population. SSP2 is characterized by development similar to historical trends, which represents an intermediate world between SSP1 and SSP3 (O'Neill et al. 2015, O'Neill et al. 2014).

The development of the water use scenarios follows the method developed in Yao et al. (2016), which links regional specified historical trends and future development targets with China's national SSPs scenarios. The water use scenarios for the upstream regions, i.e. Guangxi, Guizhou, Yunnan, and Guangdong without the delta, are generating using the national assumptions and planning targets for China during the period 2010-2050 (Wada et al. 2016). Quantitative assumptions for China's population and GDP growth are compiled from the SSPs database[12], the IIASA-VIC v9 and OECD Env-Growth v9,

[12] www.iiasa.ac.at/web/home/research/researchPrograms/Energy/SSP_Scenario_ Database.html

respectively. Changes in value-added manufacturing are derived from the UNEP GEO4 Driver Scenarios (Rothman et al. 2007).

Scenarios for the delta are adopted from the study in Chapter 4, which constructed these scenarios within the context of China's overall development, but adjusted the national assumptions by taking the PRD-specific historic trajectories and planning targets into account.

Water use projections

When I refer to "SSP scenarios" below it indicates the sub-basin scenarios developed for the present study, rather than the original SSP scenario descriptions (O'Neill et al. 2015).

Sectorial water use for upstream regions and the PRD is projected using the SSP Scenarios. For each of the three SSPs, four socio-economic indicators are used to project the future sectorial water use: (1) economic development (GDP), (2) population growth, (3) structural GDP changes determined by the share of the manufacturing value-added in the total GDP, and (4) annual technological change rate. Water use is calculated for each region for three different sectors: manufacturing water use (MWU), domestic water use (DWU), and irrigation water use (IWU).

Equations from the WaterGAP 2.2 are used (Flörke et al. 2013, Muller Schmied et al. 2014) to quantify the future pathways of domestic and manufacturing water use for each upstream province and the PRD. Parameters for calculating the domestic water use were calibrated with respect to historical water use data following the methods reported in Chapter 2.

The provincial manufacturing water use intensity of 2010 (the base year) is used to project the future manufacturing water uses. My projection only captures part of the industrial water use in the PRB, because the industrial water use includes also the water use for thermal electricity generation. For instance, in the PRD, the thermal electricity generation uses about half of the total industrial water.

Water use for electricity generation is not included in this study because none of the essential data required for estimating water use in the electricity generation sector is sufficiently available for the PRB (Yao et al. 2017). One of the reason I use the WaterGAP is that it can disaggregate the manufacturing sector into an industrial sector and electricity generation sector.

Irrigation dominates the agricultural water use in the PRB. Although the details such as land use change, and irrigation system adopted are not reported comprehensively, the irrigation water use intensity in m^3 per hectare is well reported for each region within the PRB. Thus, here I use the improvement of the reported irrigation water use intensity (IWI) of the base year (per hectare water use) to estimate the effects of technology on irrigation water uses. The technological transition for irrigation was assumed following a similar rate as same as the assumption used in Chapter 4. The irrigation water use is then calculated by multiplying irrigation water use intensity (IWI) with the irrigated area. In addition, irrigation land use change scenarios are gathered from the 30-meter Global Land Cover Dataset (GlobeLand30) projection for three different SSPs (Brovelli et al. 2015). See Chapter 4 for details on how irrigation water use is calculated for each region in the PRB.

The socio-economic status of the basin in 2010 and overview of quantitative scenario assumptions of GDP, manufacturing value-added, population and irrigated area are provided in the Appendix G.

Technological improvement

All three water use sectors, irrigation, domestic and manufacturing are affected by technological change (TC), leading to improvements in water use efficiency (i.e. output per unit of water) and thereby decreasing water use intensity (i.e. water use per unit of output in the respective sector). TC estimation was quantified as annual technological improvement rates for each of the combinations of SSPs and Hydro-Economic (HE) classifications using a range of historically observations (Wada et al. 2016). See Chapter 4 for details on how to quantify TC estimation.

5.2.3 Water allocation strategies in the PRB

Four different water allocation strategies are defined. The first two strategies reflect the competition between upstream regions and the Delta, and the third and fourth strategies are two economic-driven strategies that reflect the competition between different water use sectors. All four strategies assume that all the requirements for domestic and environmental water use are fulfilled. First, environmental flow is calculated using a simple Tennant method (Pastor et al. 2014). Additional water to prevent saltwater intrusion is not included in the environmental flow calculation in this Chapter.

The four strategies are:

1. upstream-prioritized (UP) strategy. The upstream region preferentially uses the amount of water as projected under water use scenarios. If its projected water use is larger than projected water availability, the upstream region would take all the available water in this region.

2. delta-prioritized (DP) strategy. In this strategy, the upstream regions release additional water to the Delta, which can satisfy irrigation and manufacturing water demand in the Delta. Yan had planned to satisfy water demand of the Delta first, and optimized the remaining water resources between different upstream regions. However, transferring water from downstream to upstream region over a long distance is very difficult to implement (Zhong 2004). Therefore, the DP strategy is simplified. In the new DP strategy, Yan assumed that each upstream region releases the same absolute amount of additional water to the Delta.
3. irrigation- prioritized (IrrP) strategy. In this strategy, the overall agricultural profit of the PRB is maximized using an open source framework for many-objective robust decision making (OpenMORDM) developed by Hadka et al. (2015). The plan with the highest agricultural profit is selected as the IrrP strategy.
4. manufacture-prioritized (ManP) strategy. This strategy is also generated by the OpenMORDM. The difference between the IrrP and ManP strategy is that the ManP strategy pursues the highest manufacturing profit.

Yan generated the IrrP and ManP strategy by using the OpenMORDM. The OpenMORDM is a useful tool to help decision makers for adaptive water management in river basins (Hadka et al. 2015). It uses 3D scatter plots and parallel coordinates plots to visualize the trade-offs between different objectives (Hadka et al. 2015). The advantage of the OpenMORDM is tested in Yan et al. (2017). In this study, the OpenMORDM employs the Borg multi-objective evolutionary algorithm (Borg MOEA) to capture the set of best trade-off solutions. The Borg MOEA is one of the top performing multi-objective evolutionary algorithms (Reed et al. 2013; Yan et al., 2017). Two objectives and three constraints are used in the OpenMORDM to evaluate the performance of the plans generated by the Borg MOEA. The two objectives are to maximize profits from agricultural and manufacturing water use. The OpenMORDM considers the two conflicting objectives explicitly and simultaneously, and discovers the Pareto approximation trade-off sets among them. The objective functions are given as follow:

$$f_{irr\_profit} = max\left(\frac{1}{|S|T}\left(\sum_{j=1}^{M}\sum_{i=1}^{N} IWU_{i,j} * X_i * I_i\right)\right) \quad (1)$$

$$f_{man\_profit} = max\left(\frac{1}{|S|T}\left(\sum_{j=1}^{M}\sum_{i=1}^{N} \frac{MWU_{i,j} * Y_i}{MVA_t \times TC_t}\right)\right) \quad (2)$$

where f_{irr_profit} and f_{man_profit} represent profits from agricultural and manufacturing water use. M is the number of months from 2010 to 2050, N represents numbers of regions in the PRB, $IWU_{i,j}$ and $MWU_{i,j}$ are the projected irrigation and manufacturing water use in the ith region at time j, MVA_t is the manufacturing value added in year t, X_i and Y_i represent the percentage of irrigation and manufacturing water use, which are used by the i[th] region at time j, I_i represents irrigation index, S represents the set of all sampled climate scenarios. T represents the number of years during 2010-2050.

YAN used three constraints are used in this study. These three constraints are the actual irrigation and manufacturing water uses should be less than the total projected irrigation and manufacturing water uses, and the total water use of all water use sectors should be less than the water availability of the PRB given as follow:

$$IWU_{total,j} \geq \sum_{i=1}^{N} IWU_{i,j} * X_i \tag{3}$$

$$MWU_{total,j} \geq \sum_{i=1}^{N} MWU_{i,j} * Y_i \tag{4}$$

$$Q_{total,j} \geq \sum_{i=1}^{N} ENV_{i,j} + \sum_{i=1}^{N} DOM_{i,j} + \sum_{i=1}^{N} IRR_{i,j} * X_i + \sum_{i=1}^{N} MAN_{i,j} * Y_i - \sum_{I=1}^{N} RET_{i,j} \tag{5}$$

where $Q_{total,j}$ represents water availability in the PRB at time j, $IWU_{total,j}$ and $MWU_{total,j}$ represent the projected total irrigation and manufacture water use of the whole basin at time j. $ENV_{i,j}$ and $DOM_{i,j}$ represent environmental flow and domestic water use of the ith region at time j respectively, $RET_{i,j}$ is the amount of water returned by the i[th] region at time j.

5.2.4 Water shortage in the PRB

D. Yan estimated water shortages under the four water allocation strategies are estimated for each region during the dry months when projected water use is higher than water availability. As the purpose of this study is to quantify how severe the water shortage is during the dry season, more attention is paid to the drier climate change scenario (RCP8.5), for which water shortages are likely to be more severe.

For the UP strategy, water shortage of each region is calculated according to Equation 6 and 7. Equation 6 is developed for regions without upstream region, for example, Yunnan.

$$WD_m = \sum_{t=1}^{T} (AW_{m,t} - WU_{m,t})/T$$

$$WS_m = \begin{cases} 0 & , WD_m > 0 \\ WD_m, & WD_m < 0 \end{cases} \tag{6}$$

where WD_m is the monthly mean difference between water availability and water use for an upstream region during 2010-2050, WS_m represents the monthly mean water shortage for the upstream region, m represents each month during a year (from January to December), $AW_{m,t}$ and $WU_{m,t}$ are water availability and water use for month m in year t, T represents the number of years during 2010-2050.

To estimate water shortage in Yunnan, the first step is to calculate the difference between water availability and water use of Yunnan. If the difference is negative, its value is considered to be the water shortage of Yunnan province. Otherwise, water shortage in Yunnan is set to be zero, and the excess water goes to its downstream region.

Equation 7 is developed for regions with upstream region(s), for example, Guangxi.

$$WD_m = \sum_{t=1}^{T} \left(\sum_{x=1}^{X} EW_{m,t,x} + AW_{m,t} - WU_{m,t} \right) / T$$

$$WS_m = \begin{cases} 0 & , WD_m > 0 \\ WD_m, & WD_m < 0 \end{cases} \quad (7)$$

where $EW_{m,t,x}$ represents excess water from upstream region x for month m in year t.

To estimate water shortage in Guangxi, Yan first calculated the summary of excess water from all the upstream regions, then compared the total water income (water availability and excess water from upstream regions) and projected water use. If the total water income is larger than the projected water use, water shortage in Guangxi is zero. The excess water goes to downstream regions of Guangxi. Otherwise, water shortage of Guangxi equals to total water income minus projected water use, and no water is transferred to its downstream regions.

In the DP strategy, water shortage of the PRD is first calculated using Equation 6. To provide enough water resource for the PRD, each upstream region releases the same absolute amount of water to the Delta. Therefore, new water uses in these upstream regions are the original projected water uses plus the amount of water released to the Delta. The rest of the calculations are the same as in the UP strategy. For the IrrP and ManP strategy, new water use for each region is generated by the OpenMORDM. Water shortage of the whole basin is then calculated based Equation 6 and 7.

5.3 Results

In this section, the projections of sectorial water use and water availability for the PRB are presented, four water allocation strategies are identified, followed by the projected water shortage, and economic development under different water allocation strategies.

5.3.1 Water scarcity in the PRB

Regional water use in the PRB

Figure 5-2 presents different trends of future water use projected for the PRD and the upstream basin. The PRD's annual water use peaks around 2030 then curves. By 2050, the total water use of the PRD increases by 10% to 22 billion m^3 on average from 20 billion m^3 in 2010.The upstream basin exhibits a steep increase of total water use in all three paths. The total water use of the upstream basin increases with more than 50% from 45 billion m^3 in 2010 to 70 billion m^3 in 2050.

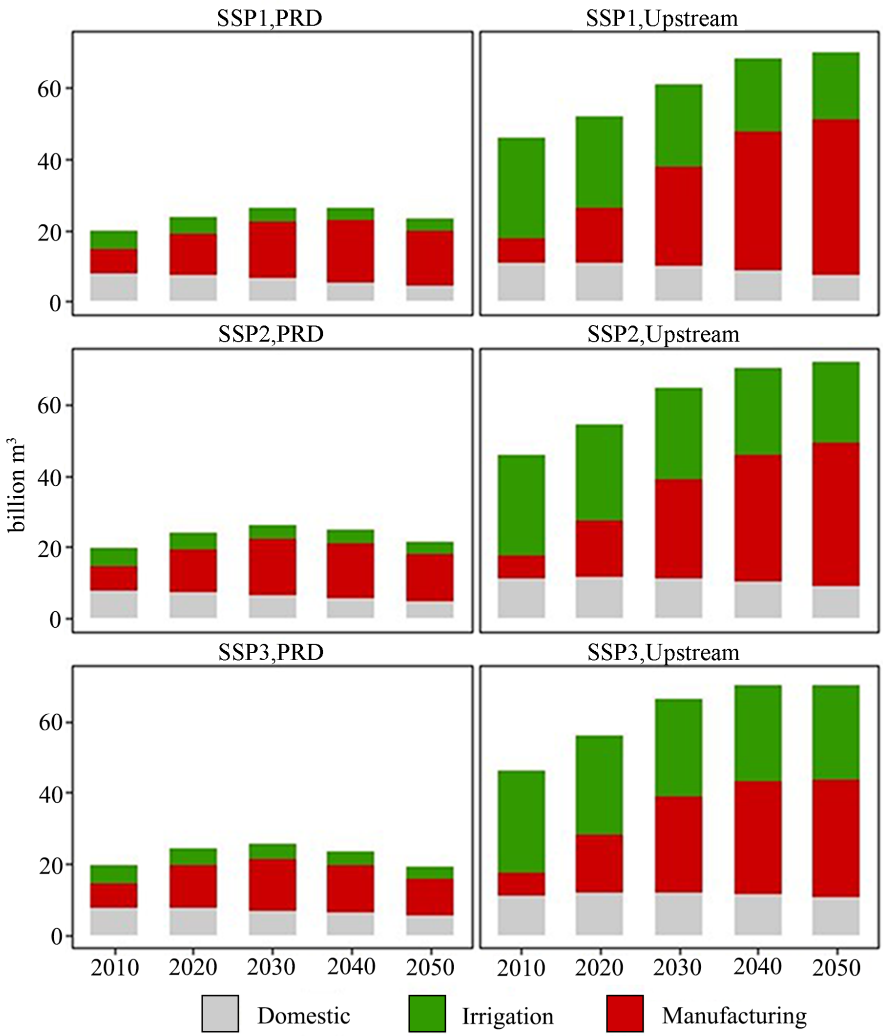


Figure 5-2. Sectorial water use projections for the PRD and the upstream PRB under different scenarios

Within the upstream areas, Guangxi and Guangdong (without the PRD) are the dominant water users, account for 54 and 30% total water use in 2010 and 43 and 33% total water use in 2050 respectively (Figure 5-3).

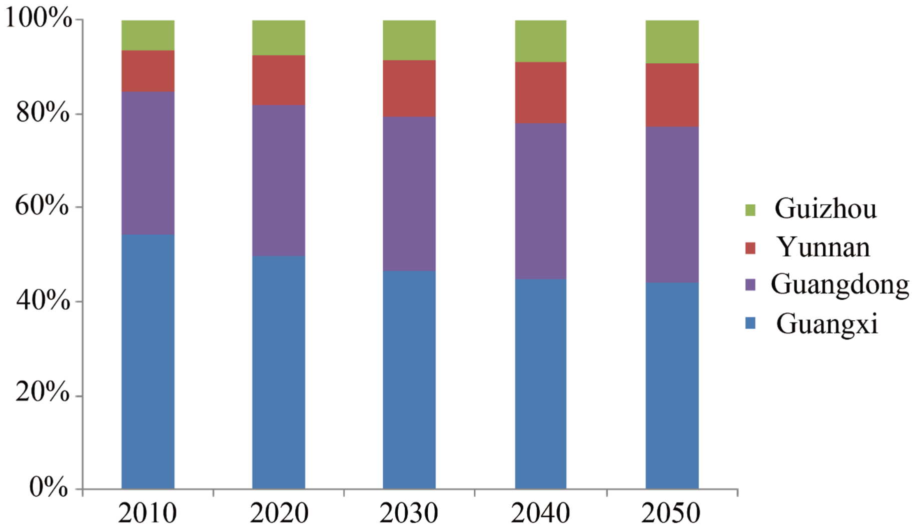


Figure 5-3. Average change in composition of regional water use in upstream basin (Guangdong in this figure is the Guangdong province without the PRD)

Sectorial water use in the PRB

The changes in future water use are largely driven by the manufacturing sector, the only sector where water use increases by 2050. By 2050, the manufacturing sector is responsible for 45% of estimated total water use in the basin.

Projections for the domestic and irrigation water use follow a consistent decreasing trend under all the scenarios across the PRB (Figure 5-2). By 2050, domestic water use will decrease by 37% (PRD) and 19% (Upstream) due to a combination of population change (the population in PRB first increases till around 2030, then decreases.) and technological improvement. Irrigation water use will decrease by 36% (PRD) and 20% (Upstream) due to improved water use efficiency as a result of technological development and a reduction of irrigated land. By 2050, the manufacturing sector dominates the total water use in the PRD, whereas irrigation water use still is a considerable fraction of the total water use in the upstream areas.

The large differences between the PRD and the upstream area are because of the different scale of irrigation sector in the base year. As the national SSP assumptions indicate, the upstream basin will continue to show rapid economic growth while retaining most of its irrigated lands. This results in a continuous increase of water use during the study period. Although the speed of increase levels off, the projection does not show a clear saturation of total water use in the upstream basin by 2050.

As Chapter 4 shows, the Delta has its own development path, where the sectorial water use will maximize around 2030 and then gradually decrease (Yao et al. 2017). By 2050, the total water use in the PRD is comparable to the level of 2010.

Water availability changes in the PRB

The decadal changes of the water availability in the PRB show a decreasing trend from the 2010s to 2040s under both RCP4.5 and 8.5 (Figure 5-4). At present about 280 billion m^3 of water is available for the upstream and about 47 billion m^3 is available for the PRD (including dry season and wet season). This means that water use is presently at 25-30% of available amounts in the upstream and at 50-60% in the downstream. In the 2040s, the total water availability of the upstream regions is 15.2 billion m^3 lower than the water availability in the 2010s under RCP4.5. Water availability in the delta reduces by 1.69 billion m^3 from the 2010s to 2040s under RCP4.5. Under RCP8.5, the water availability of the upstream regions and the Delta reduces by 10.4 and 2.25 billion m^3 from the 2010s to 2040s respectively. The water availability under RCP8.5 for each decade is lower than the water availability under RCP4.5 for the whole basin. In the upstream regions, the difference in water availability can reach up to 4.68 billion m^3 between RCP4.5 and 8.5.

Water shortages in the PRB

Future water availability and water use projected for the PRD and the upstream regions are compared. The comparison only focuses on the dry months when projected water use is higher than water availability. The comparison reveals water shortages exist for the period of 2010-2050. The average decadal water shortages of the upstream regions and the Delta show an increasing trend, which is opposite to the trend of the water availability. The annual average water shortages for the whole upstream region and the Delta under the assumption that each region in the PRB is an independent system are shown in Figure 5-5. For the Delta, water shortages are around 500 million m^3 per year. The upstream region's total water shortage is twice as much as the water shortage in the PRD. Results also show that water shortages under RCP8.5 are much higher than water shortages under RCP4.5 for the whole basin under all the SSPs. However, the differences in water shortage between different SSPs are not substantial in the PRD. For the upstream region, water shortages under SSP3 are clearly higher than water shortages under SSP1 and 2.

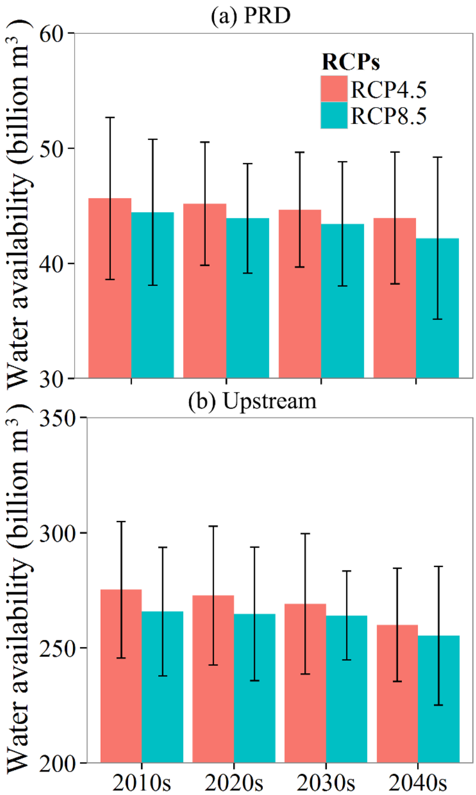


Figure 5-4. Annual average water availability for each decade from 2010s to 2040s under RCP4.5 and 8.5. The error bars indicate minimum and maximum values of the five climate models

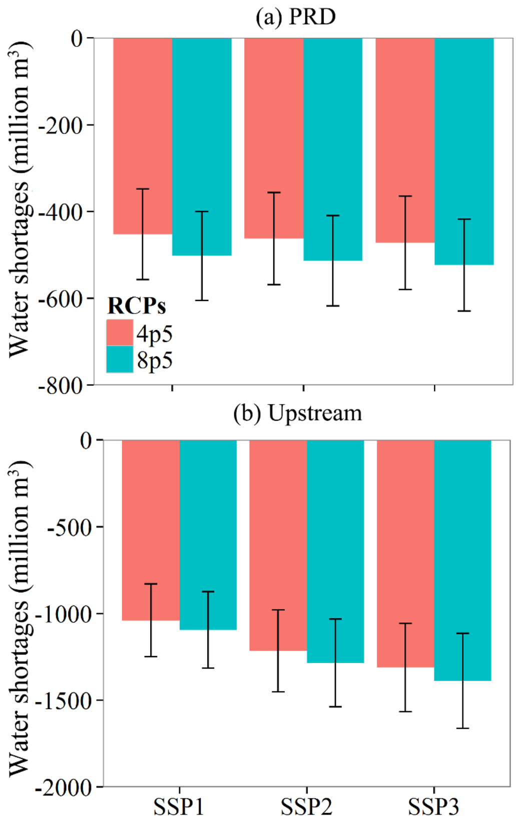


Figure 5-5. Annual average water shortages for the PRD and the upstream PRB under different RCPs and SSPs (2010-2050). The error bars indicate minimum and maximum values of the five climate models

5.3.2 Identifying water allocation strategies

Figure 5-6 illustrates an example how to identify the IrrP and ManP strategy using the OpenMORDM under RCP8.5 and SSP1. The OpenMORDM generates a set of alternative plans with different agricultural and manufacturing profits based on the two objectives and three constraints mentioned in Section 5.2.3. Since the main purposes of the IrrP and ManP strategy are to pursue maximum agricultural and manufacturing profits, the two plans that yield the highest agricultural and manufacturing profits were selected manually as the IrrP and ManP strategy respectively. In other words, the OpenMORDM generates many possible plans, but here we only discuss the most extreme plans. The same method was used to obtain the strategies for SSP2 and SSP3.

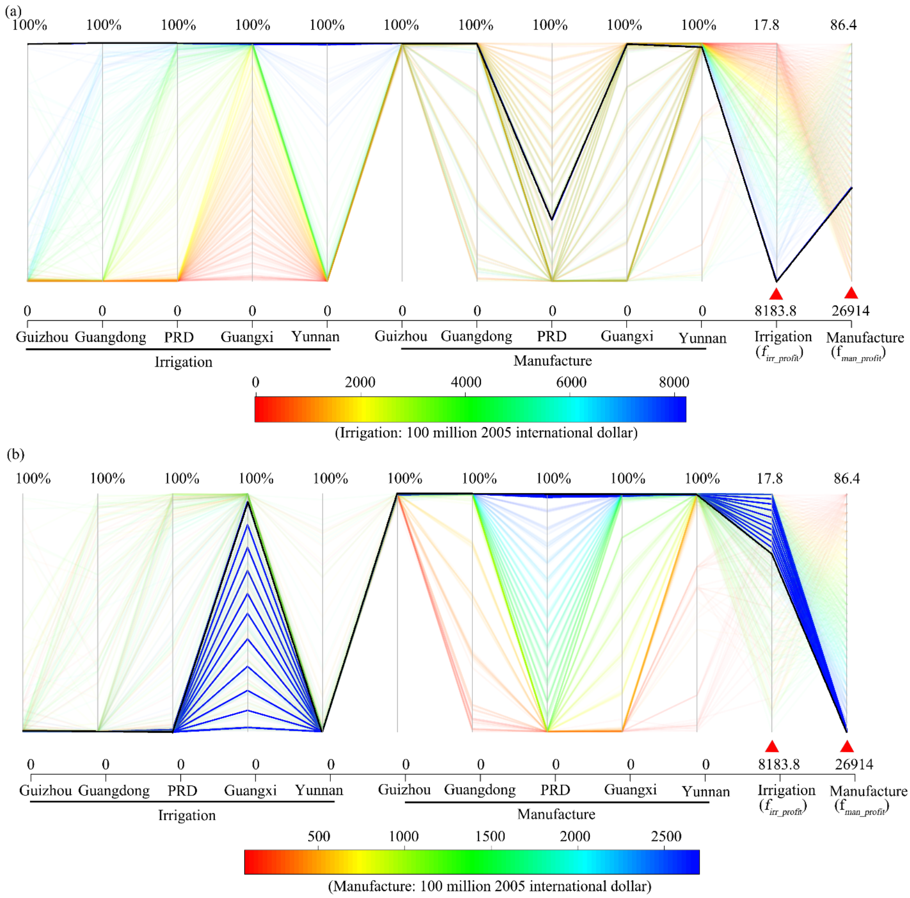


Figure 5-6. Selection of the IrrP and ManP strategy under SSP1 and RCP8.5: (a) the IrrP strategy, (b) the ManP strategy. Each line represents an alternative plan where its intersections on the vertical axes represent the percentages of projected water use, which would be used in different regions for different purposes. The red triangles represent ideal values for the corresponding objectives. Plans are coloured based on (a) irrigation and (b) manufacturing profits respectively. The black line is the selected plan

5.3.3 Water shortages under different water allocation strategies in the PRB

As shown in Figure 5-7, Yunnan, Guangxi, Guangdong and the PRD are likely to face severe water shortages under the UP strategy. Yunnan is the province with the highest water shortage, where an additional 300 million m^3 of water is needed each month during January-April period for all SSPs. For Guangxi, Guangdong and the PRD, water shortage is higher during the period of November-December than January-April. In the PRD, water shortage can reach up to 255 million m^3 in December under SSP3. Results also show that only subtle differences in water shortage are found between different SSPs.

Water shortages for all the regions except Guizhou are lower under SSP1 compared to SSP2 and 3.

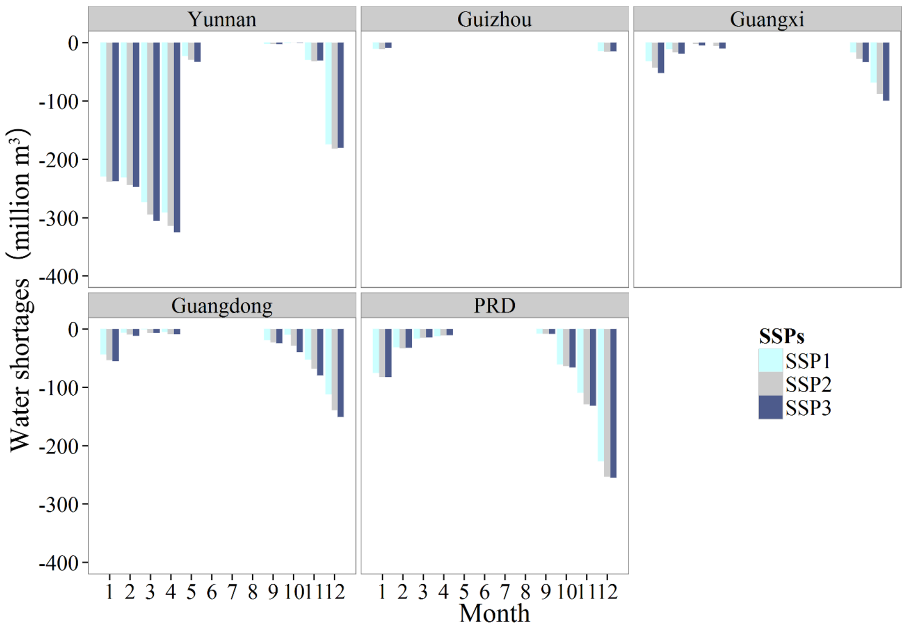


Figure 5-7. Average monthly water shortages for different regions in the PRB under the upstream-prioritized strategies for the period of 2010-2050 (RCP8.5)

Under the DP strategy, water shortages for all the upstream regions have become larger compared to water shortages under the UP strategy, except for the PRD (Figure 5-8). Additional water from the upstream regions is sufficient to supply all the water uses in the delta, but increases upstream shortages. Under SSP3, all the upstream regions expect Guizhou have the highest water shortages. In Guizhou, water shortages under SSP2 are higher than water shortages under SSP3. Figure 5-6 shows what percentages of projected irrigation and manufacturing water uses can be satisfied for each region under the IrrP and ManP strategy. The part that cannot be satisfied under the projected water availability is considered as water shortage of the region (see Section 5.2.4). Figure 5-9 shows the annual average water shortages for the whole basin under three SSPs. Water shortages range from 800 to 1500 million m^3 under both IrrP and ManP strategy. Under SSP3, water shortage in the PRB is more severe than under SSP1 and SSP2. Under all three SSPs, water resources in the PRB are insufficient to satisfy both irrigation and manufacturing water uses.

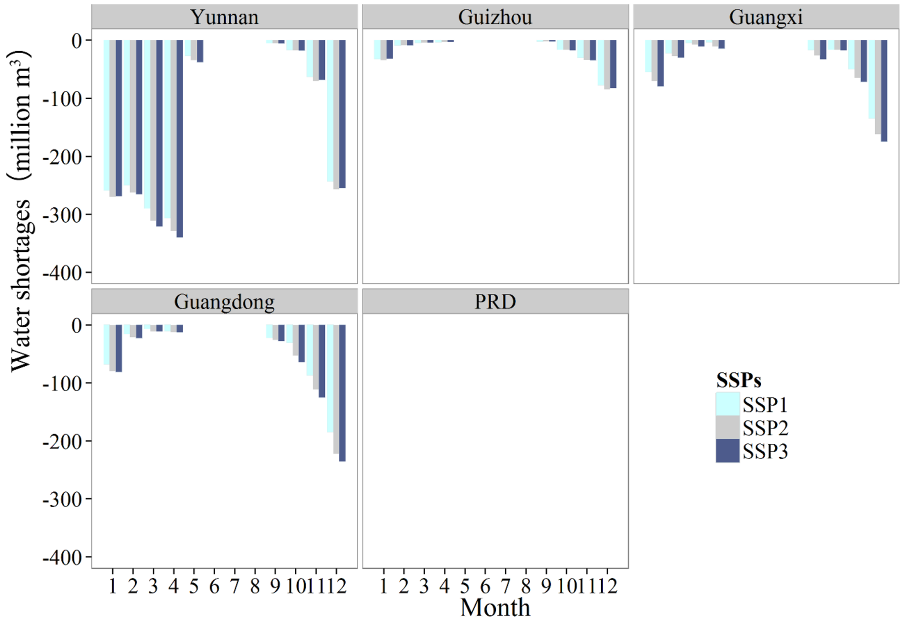


Figure 5-8. Average monthly water shortages for different regions in the PRB under the Delta-prioritized strategies for the period of 2010-2050 (RCP8.5)

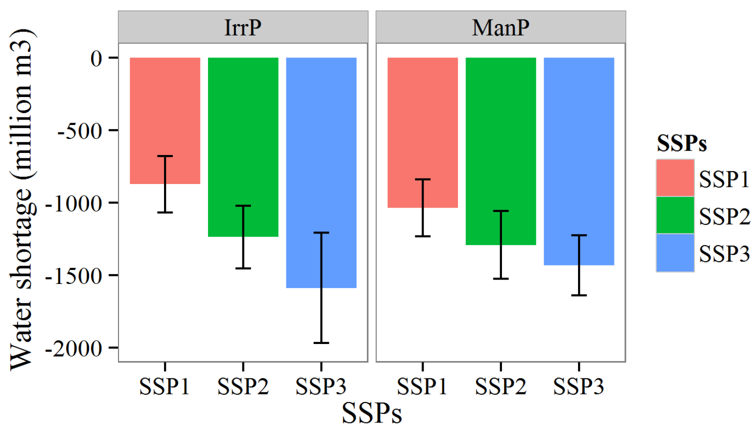


Figure 5-9. Annual average water shortages under the IrrP and ManP strategy for the period of 2010-2050 (RCP8.5)

5.3.4 Economic development under different water allocation strategies

The economic profits of agriculture and manufacturing sector under the condition with no water stress are selected as the baseline, i.e. under the baseline, both the upstream and the PRD will achieve the socio-economic development suggested by the SSPs scenarios (on average 4682 and 4146 billion international $2005 for the upstream regions and the PRD respectively), regardless if enough water is available in future.

Figure 5-10 shows the average economic losses due to water shortages compared to the baseline under different water allocation strategies. The error bars indicate minimum and maximum values of the five climate models. We found that economic losses for the PRB differ greatly under the four water allocation strategies. The PRB has the highest economic losses under the IrrP strategy, up to 14% of the total projected GDP of the whole PRB in 2050. For two strategies that reflect the competition between the upstream regions and the Delta (the UP and DP strategy), the PRB has higher economic losses under the UP strategy. The economic difference between the UP and DP strategy can reach up to 450 billion US$ under SSP1. Results confirm that although the economic growth rate of the upstream region is projected to have a large increase in the future, it is still weak when facing the competition from the PRD. Another interesting finding is that the economic losses under the DP strategies is higher than economic losses under the ManP strategies. This result is different from expected. The reason will be discussed in Section 5.4.

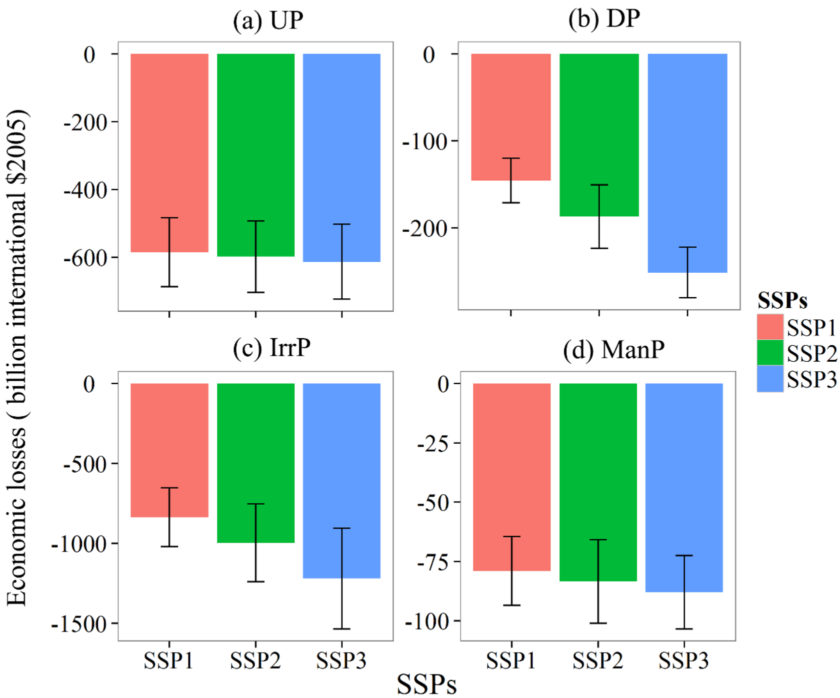


Figure 5-10. Average economic losses for the whole Pearl River Basin under four different water allocation strategies in 2050 (RCP8.5) (a) the upstream-prioritized, (b) the PRD-prioritized, (c) the irrigation-prioritized, and (d) the manufacture-prioritized strategy. Note different scale of y-axis of the different panels

5.4 Discussion

5.4.1 Projected water shortage

This study shows that the PRB is likely to face water shortages under all projected scenarios (Figure 5-5). It is the result of both increasing water demand and decreasing water availability. For example, water demand of the upstream regions increases by 25 billion m^3 from 2010 to 2050. During the same period, the total water availability of these regions decrease by 10.38 billion m^3 under RCP8.5. The increasing water demand contributes twice as much as the decreasing water availability to water shortage. The result is consistent with previous studies about the PRB. Yang et al. (2008) concluded that water shortages in the East River basin (a major branch of the PRB) are aggravated by both climate change and human activities. Similar conclusions about the causes of water shortage in the Delta are drawn by Yao et al. (2016). It should be noted that water shortages in the PRB are seasonal events. There is sufficient water supply for the PRB during the wet season. However, storing large amount of water in reservoirs may lead to increasing flood risk as more than 80% of streamflow in the PRB occurs during the wet season.

Figure 5-5 suggests the differences in water shortage between RCPs are larger than differences between SSPs. The error bars in Figure 5-5 indicate that uncertainty in GCMs are larger than uncertainty in RCPs. To sum up, uncertainty in SSPs < RCPs < GCMs. Yan et al. (2015) explored uncertainties existed in different GCMs and RCPs. In this study, more attentions were paid to the three SSPs. Furthermore, in order to obtain the upper limits of the water shortage, the results under RCP8.5 were selected for further analysis in Section 5.3. Differences in water shortage between different SSPs are not significant based on my water use projections. Because the study period is relatively short spanning for only 40 years during which the socio-economic development under different SSPs pathways are not diverged significantly from each other. The water shortages are slightly higher under SSP3 (Figure 5-5). This is consistent with the narrative of the shared socio-economic pathways. The SSP3 is a pathway that faces high challenges both in mitigation and adaptation. Under SSP3, the economic development is primarily regionally oriented, and economic development and technological change are more fragmented and slower than SSP1 and 2 (O'Neill et al. 2014). In addition, the SSP3 is also characterized by rapid population grow. Low water use intensity due to slow technological change, together with high domestic water demand, make SSP3 the most water consuming scenario.

The OpenMORDM generated many possible water allocation strategies. In the real world, selection of water allocation plans requires stakeholders from different sectors to reach a compromise between the objectives. All the water users in the PRB should be given a fair treatment. But in this paper, only the most extremes ones were discussed. The performance of the four water allocation strategies was evaluated in this study. Results show that none of the prioritization strategy is sufficient to avoid all economic losses caused by water scarcity in the PRB (see Section 5.3.4). Prioritizing water for the delta and manufacture sector are the most profitable water allocation strategies.

The purpose of the "Key Reservoirs Operational Project for the Pearl River Basin" is to transfer upstream fresh water to the delta to repel saltwater intrusion and ensure water supply safety for the delta (He 2007, Xie 2007). This policy is actually a delta-prioritized strategy. In this study, D. Yan also defined a delta-prioritized strategy, which is upstream regions give sufficient water to the PRD. Each upstream region share the same absolute amount of additional water. In this case, the pressure for Yunnan is much higher than Guangxi. Figure 5-7 and 5-8 show that Yunnan province is likely to face the worst water scarcity compared to other regions in the PRB, especially in spring. This result is consistent with some previous studies (Jia and Pan 2016, Wang and Meng 2013). As a matter of fact, drought in spring is a major and frequent natural disaster in Yunnan province. Over the last three decades more droughts have been observed in Yunnan province (Abbas et al. 2014). Hence, it is likely that Yunnan does not have the ability to provide more water for the downstream regions in the future.

Figure 5-10 shows that the ManP strategy has lower economic losses compared to the delta-prioritized strategy. It is because the additional water from the upstream regions is also used to satisfy the agricultural water uses in the Delta under the delta-prioritized strategy. In 1979, the area of irrigated land in the PRD was 13838 km^2, accounting for 25.5% of the total area. The proportion of irrigated land in the PRD decreased from 25.5% in 1979 to 16% in 2009, accompany with a rapid increase of construction land (Liu et al. 2016). In Section 5.3.1, agricultural water uses in 2050s reduce around 60% compared to agricultural water uses in 2010s due to improved water use efficiency as a result technological development and a reduction of irrigated land. Nevertheless, the agricultural water use still account for more than 10% total water use in 2050s (Figure 5-2). Water allocation between upstream regions and the PRD requires a compromise between economic profits and equity in the future. In addition, food security is also a high priority in China. Water resources tend to be transferred from low-value agricultural uses to high-value manufacturing uses in the PRB. In many parts of the PRB, Water shortages are limiting agricultural development (Khan et al. 2009). Since the PRB is one of the most important granaries in China, the local government must first consider the increasing food demands before implementing a policy.

5.4.2 Study limitations and outlook

The primary limitation comes from the missing sectors and detailed sub-sectorial information. Data limitations for the thermo-electricity sector make it very difficult to associate this sector with the SSP storylines in a consistent way. However, this maybe more important for water quality (i.e. temperature) considerations than for water quantity stress, since most of cooling water intake returns to the river again (Fthenakis and Kim 2010, Inhaber 2004).

Moreover, uncertainty lies in both estimation of manufacturing water use intensity and manufacturing products. Manufacturing water use intensity and economic gains heavily depend on the structural composition of this sector and the corresponding technology it adopts. However, no sub-sector water-use data is available. And it is unlikely that the industrial structure in the upstream basin will remain the same for the coming few decades given its fast industrialization process. Thus, the current projection of manufacturing water use and products may need to be updated when future long term plans become available.

As the two-child policy has recently been issued, it is unclear how much the projected population growth may differ from the real development in the coming few decades. Although, the possible estimated domestic water use may have only limited impact on future water deficit in the PRB, because the total water use is dominated by agricultural and manufacturing uses for the whole PRB.

5.5 Conclusion

In this Chapter, the effect was evaluated of four water allocation strategies on water resources and economic development in the PRB under regional scenarios that are consistent with the global scenarios developed in the context of the fifth IPCC Assessment Report framework.

Results show that future demands for water are much higher than supply. Large scale increases in water demand are mainly from manufacture factor in the upstream Pearl River Basin. Furthermore, differences in water use and shortage are not substantial between the SSPs for the whole basin. Under SSP3, the basin has the highest water shortage. Results also show that almost all the regions in the PRB are likely to face water shortage under the four water allocation strategies due to combined effects of climate change and socio-economic development in the future. The delta region only has sufficient water resources under the delta-prioritized strategy. The economic losses differ greatly under the four strategies. Prioritizing the delta region or manufacturing production would result in lower economic losses than the other two strategies, whereas the economic loss is the highest when water for irrigation has the priority. All four water allocation strategies are insufficient to solve the water scarcity in the PRB. However, all of them are rather extreme strategies. Development of water resources management strategies requires a compromise between different water users. In addition, new technologies and increasing water use efficiency is important to deal with future water shortage in the PRB.

6

Chapter 6

Synthesis

6.1 Introduction

Water use has rapidly increased over the last decades to meet the growing demand for food and industrial products, resulting from an ever growing world population and increasing living standards. Overuse of surface water has been reported for various regions all over the world, leading to doubts on the long-term sustainability of water supply (Wada et al. 2014). Climate change can exacerbate the situation by altering the natural hydrological cycle (Haddeland et al. 2014, Santos et al. 2014). Water is "second only to energy in serious problems that threaten humanity" in the future (Dong et al. 2013). Water shortage is not only one of the major challenges at present, but will also be more critical in the future in many regions in the world (Biemans et al. 2013, Mancosu et al. 2015, Martin-Carrasco et al. 2013, Milano et al. 2013, Ouda 2014, Shen et al. 2013)

The main theme of my thesis is water shortage under future climate change and socio-economic development, and possible adaptation strategies in a heavily urbanized delta area: the Pearl River Delta (PRD) in China. I focus on water use and its management.

The PRD, located in southeast China, is a water abundant monsoon region, receiving 1700mm average annual precipitation. Nevertheless, cities in the delta area suffer water shortage. Water shortage events are reported more and more frequent over the last decades, especially during the dry season (Chen and Chan 2007, Chen 2006a, Liu et al. 2010, Tu et al. 2012).

My study explored the potential water shortage and possible adaptation strategies by achieving two research objectives:

1. *To quantify future sectorial water use developments and potential water deficits in the PRD*
2. *To explorer strategies to reduce and adapt to the projected water deficits.*

These research objectives were addressed in line with the framing in Figure 1-3. In the synthesis below, different aspects of modelling and projecting the sectorial water use under climate change and future socio-economic development in a heavily urbanized river basin are discussed, and illustrated by the results from this thesis.

In Chapter 2, I first developed a conceptualization of water use based on equations used in global water resource models. With this conceptual framework, I assessed the driving forces underlying water use changes in the domestic, industrial and agricultural sector for the whole PRD, as well as for each of the nine cities that constitute the PRD separately. This assessment obtained the first comprehensive overview of sectorial water use in relation to its socio-economic drivers in the PRD between 2000 and 2010 (Section 6.2).

The reported water shortage events in the PRD were caused by seasonal salt intrusion. Low discharge (Kong et al. 2011, Zhu et al. 2007) and continuous large scale dredging (Han et al. 2010, Luo et al. 2006) were reported as the main causes of severe salt intrusion. In Chapter 3, I further examined to what extent water use contributes to salt intrusion and freshwater shortages by first quantifying monthly sectorial water use and next comparing its effects on discharge with thresholds from the graded salt intrusion warning system. Additionally, I asked and answered whether management of water use, rather than water supply, can be part of mitigating salt intrusion (Section 6.3).

After obtaining insights on current water use status and its impact on reported water shortage events in the PRD, I started to investigate how much water the PRD will use in the future. In Chapter 4, I generated a set of regional water use projections for the PRD, consistent with the global water-use projections developed in the Water Futures and Solutions initiative (WFaS), which build on the Shared Socioeconomic Pathways (SSPs) of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5; Section 6.4).

The research presented in this thesis is part of the thematic JSTP[13] project "Working with Water: adaptive land use and water management in the Pearl River Delta under climate change and sea level rise". Under this umbrella, in Chapter 5 I worked together with YAN Dan, whose research focussed more on hydrology and water availability in the PRB, to assess potential future water shortages and their impacts in the Pearl River Basin. The three water use scenarios I developed for the PRB were then confronted with water availability projections by YAN. Together,

[13] Joint Scientific Thematic Research Program (JSTP), a research Dutch Chinese research fund

we evaluated four extreme water allocation strategies that prioritized different water users. (Section 6.5)

Finally, strengths and limitations of the used methodology are discussed in Section 6.6, followed by a discussion of possible implications of my research for defining a sustainable development strategy for the Pearl River Delta and the wider Pearl River Basin (Section 6.7). Contributions of this thesis to the science of sustainable water resource management and socio-economic scenario analysis are discussed in Section 6.8. This chapter closes with perspectives on further future research in Section 6.9.

6.2 Water use of a heavily urbanized delta region

Socio-economic development affects the available water resources both quantitatively and qualitatively (Eliasson 2015). Socio-economic development also affects water uses, especially in fast urbanizing regions such as the large cities in China (Hanasaki et al. 2013, Liu et al. 2014a, Wu and Chen 2013). Gaining insights on the underlying forces driving sectorial water uses is crucial to understanding how water use will develop (Bijl et al. 2016).

The Pearl River Delta (PRD) experienced during the last few decades a scale of urban expansion and industrialization unprecedented in the history of the country (Seto et al. 2002). These studies suggest that water shortages will occur in the PRD because of the rapid population growth and economic development (Guneralp and Seto 2008).

However, a comprehensive overview of sectorial water use based on detailed and consistent information is lacking for the PRD. It is also unknown whether water resource is, or will be a limiting factor in the socio-economic development in the PRD. Therefore, PRD's present situation of sectorial water use and its major trends during the last decade were assessed.

In this thesis, a simple conceptualization of water use was developed based on equations from the global water use model WaterGAP2, to connect the sectorial water use with better documented socio-economic factors, include GDP, population, industrial value-added (IVA), and incomes. The total annual amount of sectorial water use was calculated for the water use sectors: industry (separated into thermal electricity production (ELE), and manufacturing industry (MAN), and urban (DOMU) and rural (DOMR) domestic sectors, and agriculture (AGR).

The result shows that, during the period of 2000-2010, the PRD managed to stabilize its annual total water use around 24 km^3. The annual water use increased from 21.2 km^3 in 2000, peaked at 25.8 km^3 in 2004, then gradually decreased to 23.6 km^3 in 2010. The decrease of annual water use after 2004 was due to the joint contributions from improvements in urban domestic water use intensity and in industrial water use intensity.

The latest data released after the publication of Chapter 2 confirm the trends uncovered therein. The PRD further improved its water use intensity, especially in the domestic and industrial sectors, and managed to keep its water use stable, despite the growing population and further socio-economic development. In 2015 the PRD used 22.7 km^3 of fresh water (Water Resources Department of Guangdong Province 2016).

Unlike most regions in the world where agriculture dominates the water use, industry (comprising manufacturing and electricity generation) is the dominant water user in the PRD, accounted for 43% of the total water use. This can also be seen in other heavily urbanized delta areas, such as the Yangtze Delta in China, which includes Shanghai and some other large cities. As China's largest economic zone and most industrialized region, industrial water use accounts for more than 80% of the Yangtze Delta's total water use (Buureau of Hydrology 2011).

Moreover, results indicate that while the domestic water use intensity in the PRB heavily urbanized delta region follows the general trends observed in global assessments, it may not reach the suggested saturation value. The general trend observed in the global assessments suggest that, the domestic water use intensity will increase with increasing household income until it reaches a certain saturation value, after which it remains stable, or even decreases despite further accumulating prosperity. In global assessments, the saturation value of domestic water use intensity of developed regions is often assumed to be comparable with the value of the United States, or Europe (Alcamo et al. 2003a). However, urban domestic water use intensity in the PRD saturated at a lower level and has started decreasing, while the rural domestic water use intensity also started levelling off. The results of Chapter 2 further show that differentiation of saturated domestic water use intensity exists even within a delta region like the PRD, with early developed cities reaching higher saturation levels than more recent developed cities. To my knowledge, no similar studies exist for other delta regions. But the results of the Chapter 2 are consistent with recent studies that suggest differentiation on saturated domestic water use intensity exists among different countries and regions (Flörke et al. 2013, Voß et al. 2009).

6.3 Impact of water use on salt intrusion

Even though the PRD managed to stabilize its absolute water use by significantly improved water use intensities, temporary water shortages still occur (Liu et al. 2010). Monsoon regions, like the PRD, may suffer from water shortages during the dry season because of the highly uneven distribution of rainfall and runoff (Lee and Wang 2014, Liu et al. 2014b, Sperber et al. 2013, Wang et al. 2013). But water shortages in densely-urbanized delta areas like the PRD is also a quality issue. When water quality degrades to levels below acceptable standards, shortage events occur. This can be triggered by pollution from (upstream) sewage, agricultural residues, or industrial wastes. But in a delta area, salt intrusion from the sea also can degrade water quality below acceptable levels (Anthony et al. 2014, Ataie-Ashtiani et al. 2013, Lu and Werner 2013). According to previous studies, the PRD's water shortage events are a result of the severe salt intrusions during the dry season (Liu et al. 2010).

This thesis shows that for the largest two tributaries of the Pearl River, the West River (Xi Jiang) and the North River (Bei Jiang), the off-stream water use can take up to 28% of the total discharge in the driest months. Water use can thus substantially affect the salt-suppressing ability of the discharge and exacerbate salt intrusion and water shortage.

Salt suppression requires sufficient discharge. However, the current engineering strategy can reduce the risk of salt intrusion, but cannot fully solve the problem, especially during extreme low-flow conditions like those in the winter of 2004.

My study shows that if the PRD can improve its sectorial water use intensities to levels that are comparable with the best practices in the world, the water saved would have a comparable contribution to preventing salt intrusion problems as the extra discharge from the Datengxia Reservoir, which is currently under construction for this purpose. Most of the freshwater inlets in the study area could be released from the threats of salt intrusion throughout the dry season even during extreme conditions. Improving water use intensity can be a promising option for the Pearl River basin to reduce salt intrusion.

When the population keeps growing in the future, the impact of salt intrusion on a heavily urbanized delta area will become more and more severe. When there is no possibility for the construction of new discharge regulating reservoirs, the policy maker will have a strong incentive to improve water use intensity by adopting cutting-edge technologies, or even consider optimizing the industrial structures. Restraining the textiles sector, for instance, might be an option for the PRD to achieve the same manufacturing water use intensity as Germany, as proposed in Chapter 3.

Although the off-stream water use management can be a promising policy option to help the delta combat severe salt intrusion, it remains an important question whether it will outweigh the continuous growth of delta cities and upstream urbanizations and resultant water use requirements. Against this background, I explored possible future water use development.

6.4 Building regional water use scenarios

Water use projections are crucially important to ensure sustainable access to fresh water, and to safeguard socio-economic activities. Many studies have assessed the impacts of socio-economic development on water use (Alcamo et al. 2007, Bijl et al. 2016, Flörke et al. 2013, Oki and Kanae 2006, Wada and Bierkens 2014). The Shared Socioeconomic Pathways (SSPs) comprise a state-of-the-art set of five future societal development scenarios (SSPS1-SSP5; (Moss et al. 2010, O'Neill et al. 2015). SSPs have been developed in the context of the Intergovernmental Panel on Climate Change (IPCC) its Fifth Assessment Report framework (Moss et al. 2010, O'Neill et al. 2014, van Vuuren et al. 2014), largely independent of other scenarios like the Representative Concentration Pathways (RCPs) that reflect the level of radiative forcing of the climate system (van Vuuren et al. 2011). Recently, the Water Futures and Solution initiative (WFaS) developed a set of water use scenarios consistent with the SSPs and RCPs, and estimated the global sectorial water use (Wada et al. 2016).

In Chapter 4, I developed two sets of regional water use scenarios for the PRD, consistent with the WFaS global assessment. With these scenarios, agricultural, domestic and manufacturing water use in the PRD was projected until 2050 using WaterGAP 2.2 (Flörke et al. 2013, Muller Schmied et al. 2014), one of the global water use models applied by the WFaS initiative.

The first set of scenarios follows the national assumptions for China used in the WFaS initiative, which reflect a homogenous future development in China. The regionally specific scenarios were built within the context of China's overall development, but adjusted the national assumptions by considering the regional historical trajectories and available future development targets for manufacturing and domestic sectors in the PRD. Agricultural water use was quantified considering a reduction of the annual agricultural water use intensity affected by technological improvement only.

In the regionally specific scenarios, total water use of the PRD will peak around 2030, then curves in SSP1-4, and stabilizes in SSP5. In 2050, the projected total water use of the PRD shows a 57% increase in SSP5 compared to 2010, whereas SSP3 expects a 5% decrease in total water use. The manufacturing sector dominates the dynamics of future water use changes. In SSP5 for instance, 74% of the estimated total water use in 2050 will be required by the manufacturing sector.

Water use in all the three sectors assessed is affected by different rates of technological improvement. Technological improvement alone could decrease agricultural water use in the PRD by 36%. Due to the joint effects of a slowing down population growth and especially technological improvements, domestic water use is projected to decrease by 38% in 2050.

When following the "national-homogenous" scenario, however, PRD's water use would double by 2050. Technological improvement also contributed most to the differences between the two sets of water use scenarios of the other sectors, relative to the other three socio-economic variables used in this study, i.e. GDP, population and share of manufacturing in GDP.

6.5 Future water conflicts, their effect on economic development, and possible alleviation strategies

As a heavily urbanized and industrialized delta area, the PRD's water use development in the future is largely determined by its economic growth, population growth, and industrial composition. Results of Chapter 4 show for most scenarios a rather positive water use projection in 2050. But the total water use of the PRD could still increase by up to 54% in 2030, improving only thereafter. However, water use is only one side of the water balance in a river basin system (Figure 1-1). Previous study indicate that both the rainfall and discharge of the Pearl River will likely decrease during the dry season due to climate change (Yan et al. 2015). In addition, the upstream region of the Pearl River Basin also develops rapidly. Given the scale of the region and its population, the competition over fresh water resources between the upstream regions and the PRD may intensify in the future. To evaluate such possible water conflicts and the potential of various management options to ease the situation, I built water use scenario for the whole Pearl River

Basin corresponding to those developed earlier for the delta only (Chapter 5). Results confirm that competition over water will intensify between different region and sectors in the PRB under future climate change and socio-economic development.

In 2010, the PRD used 20 km^3 fresh water, while the upstream basin of the PRB used 45 km^3. By 2050, the average water use projection under SSPs show that the PRD needs about 2 km^3 more water, while the upstream basin needs 25km^3 more water, or about 50% more than in 2010. At the same time, the average water resource availability of the upstream basin and the PRD shows a decreasing trend under both the RCP4.5 and RCP8.5 scenarios. During the 2040s, the total water availability of the upstream basin and the PRD could decrease by up to 15 km^3 and 2 km^3 in comparison with 2010s, respectively.

As the result, by 2040s, the annual water deficit in the PRD could be around 500 million m^3, while the water deficit in the upstream basin would be twice that of the PRD. Although these figures are based on the assumption that different regions in the PRB are independent systems (no income flows between regions), the results clearly show that water will become a limiting factor for the PRB to sustain its socio-economic development. To achieve the socio-economic development as suggested by SSPs, or to sustain the current development trends, the PRB will need to find an optimal water management strategy.

All 4 (rather extreme) water allocation strategies proposed in Chapter 5, i.e. the upstream prioritized strategy, the delta prioritized strategy, the irrigation prioritized strategy, and the manufacture prioritized strategy, are insufficient to solve the water scarcity in the PRB. Almost all the regions in the PRB are likely to face severe water shortages in future. Even if the “PRD prioritized” strategy will be adopted, which means the whole upstream basin needs will be sacrificed to secure the PRD’s fresh water use, it still may get insufficient water in a dry December.

In terms of economic loss, a rough estimation for manufacturing and irrigation sectors shows that under the PRD prioritized strategy, the economic loss of the whole PRB could reach nearly 30 billion international $2005. This figure could be doubled if the upstream competes for water resources with the PRD. The PRB faces the highest economic losses up to 122 billion international $2005 when prioritizing water use for irrigation. The economic loss could be 10 times less, down to 8 billion international $2005 if priority is given to manufacturing production.

The overall result of Chapter 5 implies that water will become a limiting factor to sustain the rapid economic growth in the PRB. It is unlikely that the PRB will get enough water to realize the economic growth suggested in the SSPs. To achieve a sustainable water resource management strategy in the PRB requires a compromise between different users within the whole basin, not only among the different sectors, but also among the different sub-basin regions.

6.6 Reflection on strengths and limitation of the study's methodology

My thesis aimed to obtain a better understanding of the sectorial water use development in a densely-urbanized delta region. I developed a conceptualization of water use to assess the contribution of sectorial water needs in the reported water shortage events in the PRD, and to explore the possibility of using water use as an adaptive measure to alleviate the risk of severe salt intrusion. Furthermore, I developed a method to generate regional water scenarios consistent with global scenario assumptions. With these regional water scenarios, I could evaluate water balance dynamics in the future, to help safeguard the access to fresh water, while sustaining the fast population and socio-economic growth.

Observational data documented in various government reports and statistic yearbooks have been collected for my study and presented in this thesis, such as sectorial water use data and water use intensities. These data are subject to uncertainties and measurement errors. Reporting the comprehensive overview of sectorial water use data is new in China, and as a result date back to only the end of 1990s. I selected the generally well documented data from 2000, but not all the sectors are covered by the report, while the statistical categorization of sub-sectors such as urban and rural domestic were modified several times.

On the other hand, however, every time when the statistical categorization is changed, the new categories suit better the developments in society. For instance, the domestic water use is changed from domestic urban and rural residential water use before 2003, to urban public water use and residential water use till 2008. Since 2009, the domestic sector has been changed into three sub-sectors: urban public water use, urban residential water use, and rural residential water use. With these new categories, my model can simulate the urban and rural domestic water use separately according to the differentiated income, and simulate urban public water use that probably relates to the overall GDP of the city. More importantly, urban public water demands could be fulfilled by recycled grey water instead of blue water from the river. That is, such new statistics, make it possible to include water re-use into the model framework.

Nevertheless, due to data limitations, my study reflects only part of the dynamics of regional water use because of an incomplete set of water using sectors selected. For example, capturing dynamics of water use in electricity production sector is not feasible with the available data. However, electricity production is the second largest water user in China following agriculture (Feng et al. 2014). In the PRD, the electricity production requires about 13% of the total water use. Population and socio-economic growth in future will directly increase the water use, but will also increase energy demand and thus indirectly further increases water use (Feng et al. 2014, Gu et al. 2016). At least some basic information on power plants is required to refine the current framework to estimate the water use for thermoelectricity production, e.g. number and installed capacity, the type of cooling system used, as well as scenarios for future power generation techniques (thermoelectric vs renewables).

Data limitation also affects the accuracy of estimated sectorial water use dynamics. Manufacturing water use intensity, for instance, heavily depends on the structural composition of the industries included in the region, and the water saving technologies adopted. Disaggregating the sub-manufacturing sectors with sufficient data, the equation used in estimating manufacturing water use could possibly be adjusted for each individual sub-sector, thus greatly increasing the accuracy of the estimation, and could thus provide comprehensive information for optimizing structural changes in the region's industrialization.

The conceptualization framework used in this thesis is largely based on equations from the WaterGAP model, a state-of-the-art global water resource model system with sophisticated modules for sectorial water use assessment. WaterGAP links sectorial water use with the underline socio-economic drivers. It is a valuable tool to capture the development trends of water use on regional level, as its input data are coarse enough to be available on regional scale, yet fine enough to capture the sectorial water use dynamics.

However, sub-sectorial scale processes and inter-(sub)sector influence is missing in the current model framework. With sufficient data support, the sectorial water use module could be upgraded with higher temporal and sub-sectorial resolution. The high-resolution estimation may provide new insights of how the sub-sectors could interact to improve the water use behaviour through cooperation, e.g. cascaded water recycling in between different (sub-)sectors.

Modelling such inter-sectorial water re-use requires intensive well-reported data of water quantity, water quality, and production processes, etc. But it is possible to start from a few key water user sectors that are the main water users. For instance, using domestic effluent or processed industrial wastewater for irrigation.

The procedure proposed in this thesis for generating regionally specific water scenarios could downscale the assumptions and data produced in global assessment, yet well capture the future dynamics on regional level. A key requirement for downscaling is to incorporate sufficient regionalyl specified development records and future targets and planning. On one hand, what is lacking in this thesis, is the long-term planning for socio-economic growth in the PRD beyond 2020, which may compromise the ability of long-term projection to capture the regional specified development.

On the other hand, regionally specified development targets may take an inward perspective only , thus overlooking the requirements of neighbouring regions. For instance, as I find in the study, neither the PRD nor the upstream PRB can achieve the SSPs suggested socio-economic development as they need to share the same limited water resources. Therefore, regionalization of the scenarios narratives and assumptions through a participatory process with regional experts and stakeholders would further improve the robustness of regional water use projections. The recently implemented “river chief” system, which established a 4-level river manager system and appoints local governors as the “river chief” responsible for the protection and management of water resources in their administrative regions. The “river chiefs” will be held accountable for any water related damage in their region. As can be imagine, to achieve the sustainable development, or to avoid possible damage, local “river chiefs” must cooperate through a participatory process, seeking a multiple-win situation for all the regions within a river basin.

6.7 Synthesis: impact of the present study to achieve a sustainable future for the Pearl River Basin

Sustainable water resources management requires understanding of water resource distribution, but also water use behaviour on regional level, including intra-annual variations (Mekonnen and Hoekstra 2016). Because in essence, the cause of water scarcity results either from the spatial and temporal mismatch between fresh water availability and water use (Postel et al. 1996, Savenije 2000), or from water quality degrading below acceptable levels (Anthony et al. 2014, Ataie-Ashtiani et al. 2013, Liu et al. 2010, Lu and Werner 2013).

This thesis showed that the current water management planning and socio-economic targets developed for the Pearl River Basin can hardly be realized under the impact of future climate change due to the rapid population and economic growth and severe competition over limited water resources, especially during the dry season.

The PRD may successfully manage its overall water use in 2050 to the same level as in 2010. But for the whole Pearl River Basin, water deficits will become more severe in the dry season (Research Objective 1)

As of 2012, over 50% of the total population in China lives in urbanized centres (Yang 2013). The government targets to reach 60% by 2020, and if the current growth rate holds, some 1 billion people could move into one of the Chinese cities (Bai et al. 2014), including those in the Pearl River Basin. The rapid urbanization will demand more and more water resources to support the expanding cities, urban populations, and all the production and services required (Kaushal et al. 2015). Sustainable development thus requires sustainable water supply not only for human activities, but also for adapting to natural hazards, for instance, the severe salt intrusion in the Pearl River Delta, where millions of people would otherwise be affected.

The results of this thesis show that the salt intrusion induced seasonal water shortage in the Pearl River Delta is not only a "natural" phenomenon, but results from the interplay between various dynamic processes, including water use (Chapter 3). Although the PRD managed to stabilize its total annual water use since late 2000s (Chapter 2), however, being in a monsoon area, the whole Pearl River Basin suffers the highly uneven temporal distribution of available water. The low flows in the dry season compromises the salt suppressing ability of the discharge. The large amount of water use further deteriorates the compromised salt suppressing ability, worsening the impact of salt intrusion induced water shortage (Chapter 3).

The PRD may be able to manage its water use in future without significant increase of total water use (Chapter 4). Combining with the large-scale hydro-engineering project of Datengxia, these joint efforts could largely alleviate the salt intrusion damage by providing extra discharge for salt suppression (Chapter 3). However, whether this "extra discharge" strategy is feasible, also depends on the upstream Pearl River Basin. The upstream Pearl River Basin is currently the most underdeveloped region in China (National Bureau of Statistics of China 2016). When the upstream basin catches up on the rapid socio-economic growth of the rest of the country, none of the examined water allocation strategy could provide enough water resource to sustain the PRB's development and provide sufficient discharge for salt suppression during the dry season (Chapter 5).

Future sustainable water management and socio-economic development requires cooperation among different water users in the PRB, and may also need to compromise the current and SSPs suggested development targets (Research Objective 2).

To sustain the water uses, or to use water use as an adaptive strategy to sustain the future socio-economic development under climate change, the Pearl River Basin is suggested to 1) drastically improve sectorial water use intensity, and 2) at the same time to optimize the industrial structure over the whole basin (Chapter 4).

Industry is the most influential water user in the Pearl River Basin. In 2010, the manufacturing accounted for only 14% of the total water use in the upstream region. By 2050, this figure is expected to reach over around 50% under different SSPs (Chapter 5). Future economic growth will inevitably increase the industrial production. When the scale of industrial production further increases, improving water use intensity is the only way to level off the corresponding increase of water use. Manufacturing water use intensity differs drastically between various industries both quantitatively and qualitatively (Voß and Flörke 2010) and preferential development of more water efficient industries will help, e.g. shifting the manufacturing production from heavily water depended industry to less water depended industry, or shifting the GDP from industry to services. Other water management options, such as water recycling within and in between different sectors, may also help reduce the overall water uses.

Technological improvement, defined as technological change rate (TC), is another worthwhile factor where lots of effort should be put in. In the presented parameterization, TC always improves the water use intensity, thus always will lead to more effective water uses and decrease the total water use.

TC also contributed the most to the difference between water use projection among different SSPs scenarios (Chapter 4). The PRD successfully managed to stabilize its total water use by significantly TC improvement in industrial and domestic sectors (Chapter 2 and Chapter 4). Nevertheless, the water use intensity of all the examined sectors in the PRB, including the PRD, have great potential to be further improved by technology. By 2020, China aims to decrease its water consumption per unit of industrial added value by 70% in comparison with 2010 (Gu et al. 2016).

Such a huge improvement target may require significant structural change in optimizing the whole industrial sector, for both manufacturing and electricity generation sectors, e.g. promoting less water dependent production, and renewable energy sources. Nevertheless, the target should stimulate the technology transition throughout the country, including in the poor upstream region of the PRB.

In addition to the per user improvement, cooperation between the upstream region and the delta area (Chapter 5), and cooperation between different sectors should be considered to optimize the uses of the limited water resources with minimal economic losses.

Efforts have already been made in exploring the potential of cross-sectorial water re-use. Irrigation with domestic wastewater or utilization of domestic idle water in urban agriculture, for instance, has been well studied (Hamilton et al. 2007, Qadir and Drechsel 2011, Smit and Nasr 1992). Research on constructed treatment wetlands that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality of e.g. livestock effluents can also be seen as a means to re-use the discharge from livestock industry instead of freshwater to fulfil environmental water demands (Knight et al. 2000). Cascaded inter- and intra-sectorial water re-use could decrease the overall water use intensity of the involved sectors in addition to the individual improvement.

6.8 Scientific contribution to sustainable water resource management and socio-economic scenario analysis

A conceptual framework to understand dynamics of regional sectorial water use

Globally, the growing water use is approaching the total renewable fresh water availability (Wiek and Larson 2012). Even for the water abundant Pearl River Basin, water resource is scarce during the dry season. Sustainable water resource management requires both water resource and water use to be managed more efficiently and effectively (Gleeson et al. 2012). To assess the sustainability of sectorial water use in large countries like China, understanding the water use behaviour of water users at the regional level, as well as on the monthly scale, is crucial. This is where my study started to contribute.

On a small scale, like a household, or in a community, or for a specific production sector, many advanced complex models exist to accurately simulate the water use dynamics. But these require intensive compilation of detailed data that are not always available on the regional level. Integrated water use model for global assessment on the other hand cannot capture the sectorial water use dynamics on the regional scale.

Therefore, my study started from a simple conceptualization of water use based on well recognized equations from global water use models (Chapter 2), and presented the first consistent and comprehensive assessment of water use in the most densely urbanized delta region in the world, the Pearl River Delta. Firstly, this conceptualization of water use provides a method to homogenize the poorly reported, scattered information and reveals the trends of sectorial water use on regional level. Secondly, it offers the advantage to explore insights of driving forces behind the trend by linking the water use with corresponding socio-economic development indicators.

My study showed that the parameters used in the global assessments need to be regionalized based on regional historical records. Well recorded sectorial water use data and corresponding socio-economic data on regional scale, and even better, on (sub-)sectorial level, are crucially important in calibrating the regional specified parameters. Otherwise the estimation may over- or under-estimate the sectorial water uses on regional scale.

To reveal the underlying causes behind the reported water shortages in the PRD, understanding of the monthly fluctuation in water use and availability is required, due to the highly uneven temporal distribution of water resource in the region. Assessing future water scarcity in the Pearl River Basin, as well as developing sustainable management strategy, also requires obtaining better understanding of monthly dynamic of sectorial water uses. This is consistent with the recent global assessment that reports that for an assessment at monthly resolution, the population suffering water scarcity increases by more than 40% compared to an assessment using only annual data (Wada et al. 2011).

Thus, I further elaborated the conceptualization of water use to the monthly scale (Chapter 3). By obtaining insights of monthly fluctuation of water use and availability, I find that the off-stream water use further deteriorates the salt suppressing capacity of the runoff, thus contributes to the salt intrusion. This shows how freshwater shortages in a complex delta region result from the interplay of dynamic processes could easily be attributed to “natural” phenomenon, thereby overlooking the contribution of human activities.

The ability to analyse the monthly water balance further allowed me to evaluate different coping strategies for solving the severe salt intrusion (Chapter 3), and development strategies (Chapter 5).

Linking scenarios across geographical scales

Together with the uneven distribution of water resources, rapidly increased water use aggravates the water shortage conditions around the globe, and increases the risk of being unable to sustain the future socio-economic growth (Jiang 2009, Taylor et al. 2013, Wada and Bierkens 2014, Wada et al. 2011). Human activities and climate change both alter the dynamic of the hydrological system on multiple scales (Haddeland et al. 2014). Expected future changes on socio-economic development and climate will, on one hand, increase the pressure on available water resources, while on the other hand, compromise the availability of water resources in many regions, as well as globally (Schewe et al. 2014). Sustainable water resource management and planning for future economic development and investigation, requires projection of both the water availability and water use to safeguard sustainable access to freshwater (Harrison et al. 2016, UN-Water 2013, Wada et al. 2016).

The impacts of socio-economic development on sectorial water uses on global scale has been assessed by several studies, including the recent estimation of global sectorial water use using a set of state-of-the-art water scenario based on the Shared Socioeconomic Pathways (SSPs), and the Representative Concentration Pathways (RCPs) (Wada et al. 2016). But there is no study yet investigates whether these global level scenarios and information generated are relevant to help achieve sustainable management goals on regional level.

Thus, I introduced a scientifically sound and feasible method to derive the scenario assumptions for regional assessment of sectorial water use by linking regional specified historical trends and future development targets with the national SSPs scenarios (Chapter 4). The results showed that the method can generate the regional water scenarios that capture the fluctuations in regional sectorial water use dynamics, and at the same time be consistent with global assessment.

The methods developed in this thesis in principle are transferable, and the results are comparable under the same global scenario study framework. However, the Pearl River Delta is rather unique in comparison with other delta areas. Taking the other two large deltas in China as example, the Yangtze Delta and the Yellow River

Delta, the methods of the present thesis can be applied on these two delta regions, but the results would be different.

Yangtze Delta is the most industrialized delta region in China, where the industry sector uses more than 80% of the water for production (Buureau of Hydrology 2011). Domestic and agriculture sectors are therefore less influential in affecting off-stream water use, despite the huge population of the Yangtze River Delta. Yangtze River Delta is also one of the oldest industrialized regions in China. The industrial structure there has been well established and developed for very long time. This implies that the future water use projection for Yangtze River Delta would 1) mostly depends on the industrial water uses, and 2) technological improvement rather than structural changes.

Moreover, difference in socio-economic development between upstream and downstream areas along the Yangtze River Basin is significantly less than of the Pearl River Basin. Competing pressures from upstream area due to future development may be less in the Yangtze River Basin, than in the Pearl River Basin.

In case of the Yellow River Basin, both the delta area and upstream basin are under-developed in comparison with the Pearl River Basin and Yangtze River Basin. Agriculture dominates the water use in the whole basin, indicating the large potential to increase, but also to improving the efficiency of industrial and domestic water uses. Moreover, the socio-economic development is relatively homogeneous across the Yellow River Basin. Thus, when applying the presented methodology, one set of basin-specific scenario may be enough for the Yellow River Basin, instead of developing two separate sets of scenarios for the upstream basin and the delta region, respectively.

6.9 Outlook and recommendations for future research

The research presented in this thesis contributed in obtaining better understanding of the sectorial water use development in a densely-urbanized delta region, under climate change and rapid socio-economic development. The conceptualization of water use, and the regional water use scenarios developed for this research provided an overview of the possibility using water use management as an adaptive measure to assess the dynamics of water balance in future, and to help safeguard access to fresh water, sustaining the fast population and socio-economic growth.

While the current study focused mostly on manufacturing and domestic sector, future research should consider an additional analysis in agriculture and electricity generation sectors when developing water scenarios. Although agriculture has become a “minor” industry in the heavily industrialized delta region, the upstream river basin still requires most water for agricultural production. When building the regional water scenarios, I only assessed possible improvements from technological changes on agricultural water use intensity, and when exploring the potential water resource allocation strategies, I focused on the economic outputs from the manufacturing sector, while food production should be secured. As the agricultural water use is jointly affected by the specific production system selected, corresponding technology adopted, and arguably the most important, the climatic conditions, future research should consider more possible processes and components in agriculture system in analysis to complete the picture. For instance, the land use change switching dryland rice to paddy rice; the technology transition adopting cutting edge irrigation system; and changing in production system using more greenhouses instead of open-field crops.

In case of the electricity generation sector, key elements such as number and installed capacity of the power plant, and type of cooling system used should be considered. Moreover, quality issue of the input and discharge from the cooling system may need to be considered, if the such regulation policy exists in the study area.

Moreover, many broader sustainability features, such as equity, employment, housing, living environment, may all affect the socio-economic driving forces of water uses, thus should be considered to incorporated into the assessment of water use.

The water use framework used in this study has the ability to obtain monthly fluctuations of water use and water availability. This provides possibility to analyse the monthly water balance, and to evaluate different development strategies.

One step further of using daily data would provide more ability in simulating more complex processes and detailed situation such as return periods, drought duration, and extreme low flow events. But in turn, such high resolution requires extensively detailed data support especially for sectorial water uses. How much value would be added by resolving daily water use, in order to support development of management options that prevent water shortage, requires future exploration.

Future research should also explore the effect of water reuse and recycling on water use management, especially the potential of inter-sectorial cascaded reuse of water resources. For many water dependent sectors, e.g. electricity generation, manufacturing cooling water, the amount of the real consumptive water use is rather small compared with the freshwater withdrawal. This might not be a problem for the upstream area as the discharged water could be withdrawn again in downstream. But for the delta area it means considerable amount of fresh water resources are "wasted" into the sea. Thus, when integrating different sectors into a chain or nested system, waste water from one component may be utilized in another component as input. Such a "sector-clustering" strategy could potentially reduce the overall fresh water demand of the whole system, and consequently alter the temporal and spatial distribution of water use.

Sustainable water resource management is one of the most important challenges for heavily urbanized river basins under rapid socio-economic development and climate change, such as the Pearl River Basin in China. Proper projection of future water use is crucial to assessing future risk of water scarcity, developing sustainable development strategies, and to safeguard sustainable access to freshwater in future.

Appendix A

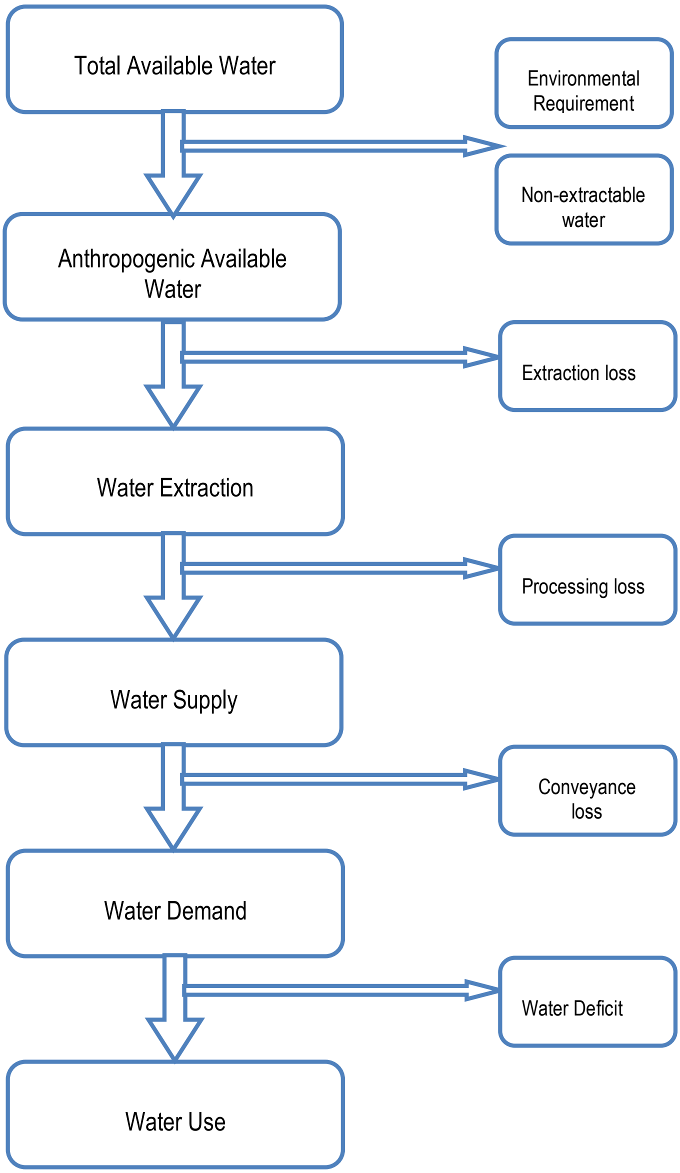
No.	Data Source	Resolution[1]	Accessed[2]	Publisher
1	China Energy Statistical Yearbook	Nat.	Nat. Lib.	NBSC[4]
2	Pearl River Water Resource Bulletin	Reg.	Online[3]	PRWRC[5]
3	Daily Surface Climate Dataset	Reg.	Online	NMIC-CDC[6]
4	Yangtze River Delta & Pearl River Delta and Hong Kong & Macao SAR and Taiwan Statistical Yearbook	Reg.	Nat. Lib.	NBSC
5	Agricultural Statistical Yearbook of Guangdong	Pro.	Nat. Lib.	Guangdong Agri. Dep.
6	Guangdong Water Resource Bulletin	Pro.	Online	Guangdong Water Resource Dep.
7	Guangdong Statistical Yearbook	Pro.	Nat. Lib.	Guangdong Stat. Bur.
8	Dongguan Statistical Yearbook	Mun.	Nat. /Pro. Lib.	Dongguan Stat. Dep.
9	Foshan Statistical Yearbook	Mun.	Nat. /Pro. Lib.	Foshan Stat. Dep.
10	Guangzhou Statistical Yearbook	Mun.	Nat. /Pro. Lib.	Guangzhou Stat. Dep.
11	Huizhou Statistical Yearbook	Mun.	Nat. /Pro. Lib.	Huizhou Stat. Dep.
12	Jiangmen Statistical Yearbook	Mun.	Nat. /Pro. Lib.	Jiangmen Stat. Dep.
13	Shenzhen Statistical Yearbook	Mun.	Nat. /Pro. Lib.	Shenzhen Stat. Dep.
14	Zhaoqing Statistical Yearbook	Mun.	Nat. /Pro. Lib.	Zhaoqing Stat. Dep.
15	Zhongshan Statistical Yearbook	Mun.	Nat. /Pro. Lib.	Zhongshan Stat. Dep.

16	Zhuhai Statistical Yearbook	Mun.	Nat. /Pro. Lib.	Zhuhai Stat. Dep.
17	Quick-speed calculation of Agriculture Handbook (Vol.2): crop cultivation (including field testing). plant protection. agricultural and water volume	Pro.	Nat. Lib.	Chemical Industry Press
18	Elementary Discussion on Water Use Efficiency of Irrigation District	Nat.	http://en.cnki.com.cn/	China Rural Water and Hydropower[7]
19	Guangdong Water Use Quota	Pro.	Online[8]	Guangdong Water Resource Dep.

1. Data availability on different spatial scales, i.e. national (Nat.), regional (Reg.), provincial (Pro.) and municipal (Mun.)
2. Data accessibility in different sources, i.e. national library (Nat. Lib.), provincial library (Pro. Lib.), and online database
3. Online data can be accessed at:
    - http://www.pearlwater.gov.cn/xxcx/szygg/
    - http://cdc.cma.gov.cn/
    - http://www.gdwater.gov.cn/yewuzhuanji/szygl/szygb/
4. National Bureau of Statistics of China
5. Pearl River Water Resource Commission
6. Climatic Data Centre, National Meteorological Information Centre of China
7. Scientific journal in Chinese. English abstract is available at http://en.cnki.com.cn/Article_en/CJFDTOTAL-ZN$_{SD}$200307009.htm
8. http://www.gd.gov.cn/govpub/rdzt/deys/

Appendix B

"Water supply" in this thesis refers to all the water provided to end users by either centralized waterworks or self-extraction. The term "water demands" and "water use" are not synonymous, as the "demand" cannot always be fulfilled when water deficit exists.



Appendix C

Research of XIONG [1] inspired development of the PRDWUM-MAN approach. In his research Xiong compared several factors affecting the industrial water use of Shaanxi Province northeast in China, and built a multi-linear regression forecast model. The affecting factors Xiong analysed in his research include industrial output (X1), ratio of heavy to light industry (X2), consumer price index (X3), water price (X4), and renovation investment (X5). Xiong's industrial water use forecast model calculates overall industrial water use of Shaanxi province as a function of the X1, X2 and X3. I performed similar analysis based on data availability of the PRD and proposed the PRDWUM-IND as equation (4). Per capita GDP is selected instead of the industrial output is because the statistics reported industrial output include the enterprises above designate size only. It means enterprises with annual profit less than 5 million RMB are not included in the statistics during the research period. Consumer price index is neglected because it doesn't provide much added value to model result. Web link in citation can access to the paper (in Chinese).

Reference of LI [2] discussed water use efficiency of irrigation in China. In this paper, the author stated that according to the national standard, the irrigation efficiency in China should be no bigger than 0.7, 0.6 and 0.5 for irrigation district of small, medium and large scale respectively. As I analyse the overall irrigation sector of the PRD without details of spatial distribution, the medium value of 0.6 is selected. This is also included as one data source in Appendix A.

Reference of LIU [3] is a calculation handbook for agricultural practices. In the second volume, it provides several location-specific crop factors (Kc) include Guangdong province. These local values are adopted while calculating the consumptive water use of irrigated crops in the PRD following FAO approach. This is now included as one data source in Appendix A.

Study of HE et al. [4] compared domestic water use intensity with national average, introduced several water-saving policies and activities that will decrease the domestic water use intensity in Guangdong province. It suggests that recently promulgated water resource management laws, regulations and raised public awareness of water saving may be the reason for disagreement between model results and WB statistics. Web link in citation can access to the paper (in Chinese).

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4. He G, Kuang Y, He D, Wu S, Deng L, et al. (2006) Countermeasures for Constructing Water-Saving Society in Guangdong Province (in Chinese). Journal of China Hydrology 26: http://d.wanfangdata.com.cn/periodical_sw200605020.aspx.

Appendix D

1. Harmonization of the Guangdong Water Bulletin data

Harmonization of industrial water uses

The absolute volume of industrial water use reported by the Guangdong Water Bulletin (hereafter WB) is the overall water use by manufacturing industry and the thermal electricity industry. But, two industrial water use intensities are reported, one for overall industry, one for the manufacturers only (without the thermal electricity generation). Thus, I calculated the absolute volume of manufacturing water uses by multiplying the manufacturing water use intensity with corresponding industrial value added. Water use of the thermal electricity generation was subtracted afterwards from the overall water use volume reported by the WB.

Harmonization of domestic water use

The original water use data from WB is released as the Table D1 in billion m^3, where DOM-Ur is the urban residential water use with urban public water use, UrbPub is the urban public water use, Resi is the residential water use in both urban and rural sectors, Resi-Ur is the urban residential water use and Resi-Ru is the rural residential water use, the latter but including also livestock water use in the data before 2003. Only two domestic water use intensity are reported however (Table D2), i.e. urban residential water use intensity and rural residential water use intensity in litre per person-day, but consistently over time.

The data collection and reporting of the available statistics change over time. The population data used in the Water Bulletin were not consistent. For most years, the "permanent population at the year-end" was used, while the "population with Hukou registration" were used in 2001 and 2002. The latter number is significantly smaller due to the large number of migrant workers in big cities like Guangzhou in China. I compute the per capita water use intensity of urban and rural sectors using the permanent population at the year-end as reported in the Guangdong Statistic Yearbook (hereafter GSY).

Thus, I adjusted the original data to ensure the comparability during the research period in the following steps.

1. Collect urban and rural population from GSY. Proportion of urban population from 2001 to 2004 are not available in GSY. Data are completed by linear interpolation.

2. Volume of rural residential water use before 2008 are calculated by multiplying per capita water use intensity IRUR from WB with corresponding rural population from GSY.
3. Urban residential water use from 2003 to 2008 are extracted from overall residential water use by subtracting calculated rural residential water uses.
4. Volume of domestic water uses are harmonized into two categories as listed in Table 2b, i.e. urban domestic water use which consist urban residential and public water uses and rural domestic water use which is the rural residential water use only.

2. Comparison between original WB data and harmonized data

Table D1. Table Absolute Volume of the Sectorial Water Use reported by WB in 10^8 m^3

	Total	AGR	IND	DOM-Ur	UrbPub	Resi	Resi-Ur	Resi-Ru	Eco-Env
2000	212.9	97.1	78.7	29.3	-	-	-	8.6	-
2001	224.7	96.6	88.8	30.3	-	-	-	9.9	-
2002	236.4	93.3	99.2	33.9	-	-	-	10.0	-
2003	249.5	91.2	107.4	-	16.3	30.6	-	-	4.0
2004	258.3	89.4	112.8	-	18.3	34.0	-	-	3.5
2005	254.7	86.4	108.5	-	13.2	39.9	-	-	3.5
2006	247.0	83.0	107.8	-	14.6	37.5	-	-	3.3
2007	249.7	81.0	104.9	-	14.8	33.6	-	-	4.1
2008	246.4	81.6	105.8	-	15.5	38.0	-	-	5.5
2009	247.5	80.9	107.0	-	16.2	-	32.5	5.0	5.8
2010	236.1	74.9	101.2	-	16.9	-	32.0	5.2	6.0

In total eight water use sectors were included, namely Agriculture (AGR), Industry (IND), Urban Domestic (DOM-Ur), Urban Public (UrbPub), Residential (Resi), Urban Residential (Resi-Ur), Rural Residential (Resi-Ru) and Eco-Environmental compensation (Eco-Env)

Table D2. Harmonized Sectorial Water Use in 108 m^3.

	Total	AGR	MAN	ELE	DOMU	DOMR
2000	212.9	97.1	-	-	29.2	-
2001	224.7	96.6	58.8	30.0	31.5	6.9
2002	236.4	93.3	-	-	34.7	7.5
2003	249.5	91.2	-	-	40.5	6.4
2004	258.3	89.4	85.0	27.8	46.7	5.6
2005	254.7	86.4	78.9	29.6	46.5	4.9
2006	247.0	83.0	79.5	28.3	51.8	5.1
2007	249.7	81.0	78.1	26.8	50.2	4.9
2008	246.4	81.6	73.3	32.5	48.7	4.9
2009	247.5	80.9	68.8	38.2	48.8	5.0
2010	236.1	74.9	70.6	30.6	48.9	5.2

Agriculture (AGR), Manufacturing Industry (MAN), Thermal Electricity Industry (ELE), Urban Domestic (DOMU), and Rural Domestic (DOMR)

Table D3. Reported Sectorial Water Use Intensity

	I_{Total} (m^3/person)	I_{AGR} (m^3/ha)	I_{MAN} (m^3/10^{4}VA)	I_{IND} (m^3/10^{4}VA)	I_{UR} (l/day)	I_{RU} (l/day)
2000	513		-	-	283	201
2001	988	11475	188	264	290	155
2002	981	11415	-	-	295	178
2003	-	10620	-	-	198	158
2004	653	12840	127	182	250	168
2005	554	12225	96	140	248	155
2006	560	11235	78	112	260	160
2007	556	12120	65	98	252	136
2008	540	11895	49	78	239	145
2009	534	11835	45	78	235	161
2010	441	9210	37	66	201	148

Table D4. Harmonized Sectorial Water Use Intensity

	I_{Total} (m^3/person)	I_{IND} ($m^3/10^4$VA)	I_{DOMU} (l/day)	I_{DOMR} (l/day)	$I_{DOM\text{-}Total}$ (l/day)
2000	496	289	269	-	-
2001	513	284	278	150	241
2002	535	264	296	169	261
2003	559	222	335	152	288
2004	572	168	374	139	317
2005	560	132	362	129	309
2006	521	106	377	146	329
2007	506	87	349	136	306
2008	480	71	323	133	286
2009	462	70	308	134	275
2010	420	53	288	148	264

Appendix E

Rank	Manufactures	PRD	Guangzhou	Shenzhen	Zhuhai	Dongguan	Zhongshan	Foshan	Huizhou	Jiangmen	Zhaoqing
1	Telecommunications Equipment, Computers and Other Electronic Equipment	22%	10%	47%	20%	25%	12%	5%	43%	5%	11%
2	Electric Machinery and Equipment	12%	6%	7%	25%	10%	20%	23%	7%	10%	
3	Production and Distribution of Electric Power and Heat Power	7%	6%	7%	10%	13%	3%	5%	4%	6%	6%
4	Transport Equipment	6%	21%		2%				3%	10%	
5	Raw Chemical Material and Chemical Products	6%	11%		5%		4%	3%	10%	6%	6%
6	Metal Products	4%	3%	3%			7%	8%	3%	14%	10%
7	Plastic	4%		3%	4%	5%	6%	5%	3%		
8	Non-metallic Mineral Products	3%						9%		4%	6%
9	Textile Garments, Footwear and Caps	3%	3%	1%	2%	4%	7%	3%		5%	4%
10	Textile Industry	3%				4%	5%	4%	2%	6%	6%
11	Petroleum and Natural Gas Extraction	3%		9%							
12	Measuring Instrument and Machinery for Cultural Activity and Office Work	2%		3%	4%	3%					
13	Leather, Fur, Feather and Related Products	2%				4%	4%		3%		6%
14	General Purpose Equipment	2%	3%								
15	Paper and Paper Products	2%				5%	3%				
16	Special Purpose Equipment	2%		2%							
17	Manufacturing and Processing of Non-ferrous Metals	2%						6%			6%
18	Food Manufacturing	2%								4%	
19	Cultural, Educational and Sport Goods	1%				3%					
20	Handicrafts and Others	1%		2%							
21	Medical and Pharmaceutical Products	1%			6%						
25	Manufacturing and Processing of Ferrous Metals	1%	4%		2%						
27	Processing of Petroleum, Coking, Processing of Nucleus Fuel	1%	5%						7%		
31	Processing of Timbers, Wood, Bamboo, Cane, Palm Fiber and Straw Products	0%									4%

Proportion of the manufacture in the overall industrial value-added

Appendix F

1. Overview of the Quantitative Scenario Assumptions

Table F1. Overview of quantitative scenario assumption of population

		SSP-CN	SSP-PRD
SSP1	2010	4.19% of IIASA-VIC v9[14] population assumption for China	100% of SSP2
	2020		99.10% of SSP2
	2030		97.59% of SSP2
	2040		96.17% of SSP2
	2050		94.56% of SSP2
SSP2	2010		Same as SSP2-CN
	2020		
	2030		
	2040		
	2050		
SSP3	2010		100% of SSP2
	2020		101.11% of SSP2
	2030		102.89% of SSP2
	2040		104.72% of SSP2
	2050		107.43% of SSP2
SSP4	2010		100% of SSP2
	2020		99.28% of SSP2
	2030		97.85% of SSP2
	2040		96.06% of SSP2
	2050		93.80% of SSP2
SSP5	2010		100% of SSP2
	2020		99.01% of SSP2
	2030		97.47% of SSP2
	2040		96.10% of SSP2
	2050		94.56% of SSP2

[14] Available at the SSP Database (secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about)

Table F2. Overview of quantitative scenario assumption of GDP

		SSP-CN[15]	SSP-PRD
SSP1	2010	8.72%	100% of SSP2
	2020	7.04%	99.67% of SSP2
	2030	4.53%	102.74% of SSP2
	2040	2.41%	107.88% of SSP2
	2050	0.86%	109.79% of SSP2
SSP2	2010	8.76%	9.23% of China's GDP
	2020	5.98%	8.98% of China's GDP
	2030	2.99%	8.73% of China's GDP
	2040	1.83%	8.48% of China's GDP
	2050	0.88%	8.23% of China's GDP
SSP3	2010	8.80%	100%% of SSP2
	2020	5.38%	99.88%% of SSP2
	2030	1.85%	96.37%% of SSP2
	2040	0.81%	92.12%% of SSP2
	2050	0.04%	86.75%% of SSP2
SSP4	2010	8.70%	100%% of SSP2
	2020	5.98%	98.94%% of SSP2
	2030	3.10%	98.63%% of SSP2
	2040	1.74%	99.92%% of SSP2
	2050	0.63%	98.79%% of SSP2
SSP5	2010	8.71%	100%% of SSP2
	2020	7.98%	100.44%% of SSP2
	2030	5.45%	111.6%% of SSP2
	2040	2.83%	129.49%% of SSP2
	2050	1.23%	141.94%% of SSP2

[15] Compiled from OECD Env-Growth v9 GDP, available at the SSP Database

Table F3. Overview of quantitative scenario assumption of technological change rate (TC)

	SSP-CN	SSP-PRD
SSP1	1.10%	1.20%
SSP2	0.60%	1.10%
SSP3	0.30%	1.00%
SSP4	0.60%	1.10%
SSP5	1.10%	1.20%

Table F4. Overview of quantitative scenario assumption of manufacturing share in the total GDP

		SSP-CN[16]	SSP-PRD
SSP1	2010	42.63%	47.46%
	2020	47.51%	42.65%
	2030	49.19%	39.17%
	2040	49.34%	36.09%
	2050	48.88%	31.60%
SSP2	2010	42.64%	47.46%
	2020	47.23%	42.79%
	2030	49.36%	38.12%
	2040	49.38%	33.45%
	2050	49.23%	28.79%
SSP3	2010	42.02%	47.46%
	2020	45.13%	42.74%
	2030	46.32%	36.74%
	2040	46.99%	30.82%
	2050	46.47%	24.97%
SSP4	2010	42.63%	47.46%
	2020	47.51%	42.34%
	2030	49.19%	37.60%
	2040	49.34%	33.43%
	2050	48.88%	28.44%
SSP5	2010	42.64%	47.46%
	2020	47.23%	42.98%
	2030	49.36%	42.55%
	2040	49.38%	43.32%
	2050	49.23%	40.86%

[16] Compiled from UNEP GEO4 Driver Scenarios, Distributed by International Futures (pardee.du.edu)

2. Contribution of difference in technological change (TC), manufacturing sharing (MAN), population (POP), and GDP on difference between water use under SSP-CN and SSP-PRD

formula = Total Water Use ~ TC + MAN + POP + GDP

Residuals:

Min	1Q	Median	3Q	Max
-0.009473	-0.004253	-0.001315	0.002454	0.014136

Table F5 Coefficients

Variable	Estimate	Std. Error	t-value	Pr(>|t|)	Sign.
TC	1.08610	0.04514	24.060	3.09e-16	***
MAN	0.39568	0.02717	14.561	4.16e-12	***
POP	-0.01304	0.17421	-0.075	0.941	NS
GDP	0.93207	0.06203	15.026	2.33e-12	***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.006893 on 20 degrees of freedom

Multiple R-squared: 0.9987, Adjusted R-squared: 0.9984

F-statistic: 3819 on 4 and 20 DF, p-value: < 2.2e-16

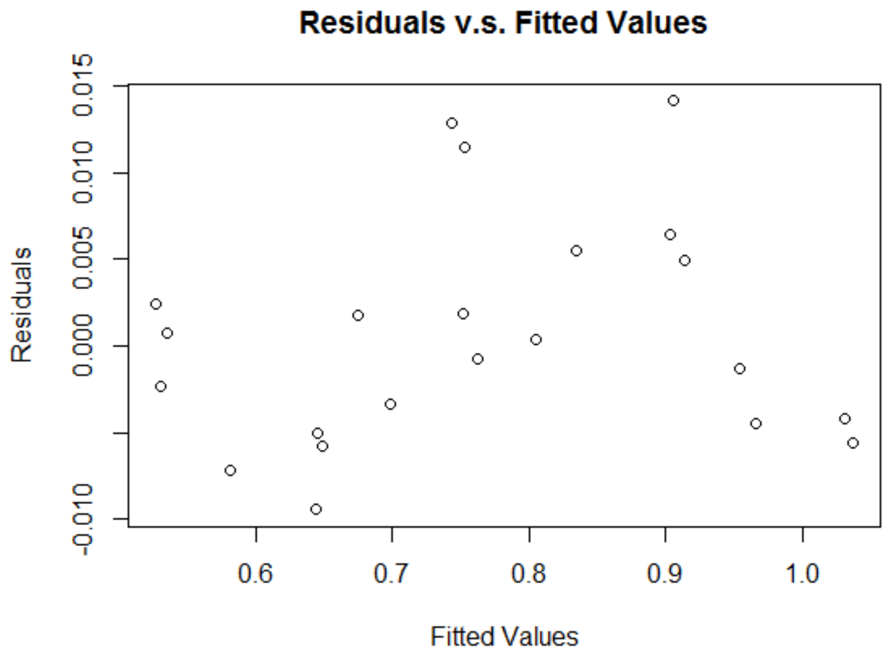

Figure F-1. Subsequent plotting of model residuals against fitted values

Appendix G

Table G1. Socio-economic status of the study area Overview of quantitative scenario assumption of population

	Guangxi	Yunnan	Guizhou	Guangdong	PRD
GDP, PPP *(100 million International $2005)*	2,175	1,642	1,046	1,901	8,426
MAN value-added *(100 million International $2005)*	877	592	345	611	3,999
GDP/ca *(international $2005/person)*	4,216	3,568	3,006	3,940	15,046
Population *(million)*	51.6	46.0	34.8	48.2	56.2

Table G2. Overview of quantitative scenario assumption of GDP in 100 million International $2005

	SSP1					SSP2					SSP3				
	Guangxi	Yunnan	Guizhou	Guangdong	PRD	Guangxi	Yunnan	Guizhou	Guangdong	PRD	Guangxi	Yunnan	Guizhou	Guangdong	PRD
2010	2,175	1,642	1,046	1,901	8,426	2,175	1,642	1,046	1,901	8,426	2,175	1,642	1,046	1,901	8,426
2020	5,016	3,787	2,412	4,384	18,231	5,038	3,803	2,423	4,403	18,311	5,054	3,815	2,431	4,417	18,268
2030	9,902	7,475	4,762	8,653	30,107	9,007	6,799	4,332	7,871	29,395	8,539	6,446	4,106	7,462	28,243
2040	15,419	11,640	7,415	13,474	39,885	12,090	9,126	5,814	10,565	36,987	10,254	7,741	4,931	8,961	34,073
2050	19,555	14,762	9,404	17,089	46,048	14,489	10,938	6,968	12,662	41,944	11,120	8,394	5,348	9,718	36,375

Table G3. Overview of quantitative scenario assumption of manufacturing value-added in 100 million International $2005

	SSP1					SSP2					SSP3				
	Guangxi	Yunnan	Guizhou	Guangdong	PRD	Guangxi	Yunnan	Guizhou	Guangdong	PRD	Guangxi	Yunnan	Guizhou	Guangdong	PRD
2010	877	592	345	611	3,999	877	592	345	611	3,999	877	592	345	611	3,999
2020	2,255	1,521	886	1,571	7,781	2,251	1,518	885	1,569	7,835	2,190	1,477	860	1,526	7,803
2030	4,609	3,109	1,811	3,212	11,772	4,206	2,837	1,653	2,931	11,206	3,797	2,561	1,492	2,646	10,362
2040	7,199	4,856	2,829	5,016	14,388	5,648	3,810	2,219	3,935	12,374	4,626	3,120	1,818	3,223	10,467
2050	9,045	6,101	3,554	6,303	14,597	6,748	4,552	2,652	4,702	12,073	4,961	3,346	1,949	3,457	9,077

Table G4. Overview of quantitative scenario assumption of population in million people

	SSP1					SSP2					SSP3				
	Guangxi	Yunnan	Guizhou	Guangdong	PRD	Guangxi	Yunnan	Guizhou	Guangdong	PRD	Guangxi	Yunnan	Guizhou	Guangdong	PRD
2010	51.6	46.0	34.8	48.2	56.0	51.6	46.0	34.8	48.2	56.0	51.6	46.0	34.8	48.2	56.0
2020	53.1	47.3	35.8	49.6	59.4	53.3	47.5	35.9	49.8	60.0	53.5	47.7	36.1	50.0	60.6
2030	53.0	47.3	35.8	49.6	58.6	53.8	48.0	36.3	50.3	60.1	54.4	48.5	36.7	50.8	61.9
2040	51.5	45.9	34.7	48.1	56.0	52.6	46.9	35.5	49.2	58.4	53.6	47.8	36.1	50.1	61.1
2050	48.5	43.2	32.7	45.3	52.1	49.9	44.5	33.6	46.7	54.9	51.4	45.9	34.7	48.1	59.0

Table G5. Overview of quantitative scenario assumption of irrigated area in ha

	SSP1					SSP2					SSP3				
Year	Guangxi	Yunnan	Guizhou	Guangdong	PRD	Guangxi	Yunnan	Guizhou	Guangdong	PRD	Guangxi	Yunnan	Guizhou	Guangdong	PRD
2010	1,285,738	321,728	237,120	560,730	614,882	1,285,738	321,728	237,120	560,730	614,882	1,285,738	321,728	237,120	560,730	614,882
2020	1,292,831	340,113	238,170	561,329	610,120	1,293,498	340,238	238,174	561,471	611,509	1,295,188	343,904	238,343	561,639	612,963
2030	1,300,681	353,630	239,136	561,979	608,233	1,303,463	355,541	239,303	562,442	610,807	1,310,105	365,636	239,987	563,187	613,919
2040	1,305,729	362,019	239,754	562,430	607,708	1,311,149	366,965	240,172	563,245	611,205	1,323,446	384,249	241,462	564,682	615,875
2050	1,308,014	365,248	240,031	562,670	608,017	1,317,463	374,890	240,877	563,987	612,229	1,335,410	398,240	242,772	566,166	617,821

Table G6. Overview of quantitative scenario assumption of technological change rate (TC)

	SSP-Upstream	SSP-PRD
SSP1	1.10%	1.20%
SSP2	0.60%	1.10%
SSP3	0.30%	1.00%

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Summary

The Pearl River is the second largest river by total discharge in China following the Yangtze River. Being situated in the subtropical monsoon area, the Pearl River Basin (PRB)is among the water abundant region, receiving annual average precipitation ranging from 1200 to 2200mm. Nevertheless, seasonal water shortages became more and more frequent over the last decades. These seasonal water shortages were caused by the severe salt intrusion. Previous studies attributed the main cause of these severe salt intrusion to low discharge and continuous dredging, but often overlooked the contribution of water use. This thesis aimed to obtain better understanding of the sectorial water use development and its impact on salt intrusion induced water shortage in a heavily urbanized river delta, and to explore the potential of water use management as an adaptation option to reduce water shortage.

The research objective of this thesis is achieved in four steps, by answering four central research questions (Chapter 1). First, historic water use was analysed, which was then used as a basis for projecting future water use under climate change and socio-economic development scenarios. Then, the potential water deficit in future and possible management strategies to alleviate the problem were explored.

Assessing water use is crucial for supporting sustainable river basin management and regional development planning. This study started with an assessment of sectorial water use in the Pearl River Delta (PRD), by analysing annual water use data from 2000 to 2010 in relation to socio-economic statistics for the same period (Chapter 2). A conceptual framework for assessing sectorial water use was developed, using the concept of water use intensity (defined as amount of water used for producing per unit of good or service), and equations used in global water resource models. With this framework, I was able to explore the driving forces underlying water use changes in domestic, industrial and agricultural sectors. The analysis was conducted for the PRD region as a whole, as well as for the nine cities that constitute the PRD.

The results show that, despite the increasing population and rapid economic growth, the PRD managed to stabilize its absolute water use by substantial improvements in industrial water use intensities, and early stabilization of domestic water use intensities. Results also revealed large internal differentiation of sectorial water use among the cities in the PRD. Industrial water use intensity varied from -80 to +95%, compared to the PRD average, whereas domestic water use intensity varied by +/- 30%.

Comparing the saturation value of domestic water use per capita for the PRD with that suggested in the global assessment, most of the PRD's cities seemed to stabilize their per capita water use at a lower value. This suggests that existing global assessments probably have overestimated future domestic water use in developing countries.

In the next step, I analysed to what extent the water use had contributed to the reported salt intrusion and freshwater shortages. In addition, I explored whether decreasing sectorial water use intensity can help mitigate the salt intrusion. To assess how much water use contributed to salt intrusion events, I first quantified monthly sectorial water use, then compared water use with threshold discharges from a graded salt intrusion warning system developed for the PRD (Chapter 3).

Sectorial water use was found to fluctuate among months. During the dry months, in which water shortages were reported, more than 25% of discharge could be withdrawn for the off-stream uses, thus exacerbating salt intrusion.

An evaluation of coping strategies showed that decreased sectorial water use intensity can significantly alleviate salt intrusion. Decreased water use intensity could reduce the overall amount of water use, thus increase the discharge by up to one threshold level in the warning system. Together with the current hydro-engineering strategy that provides extra water supply, decreased water use intensity could prevent most of the salt intrusion events in the PRD even during the dry months.

Next, I investigated the PRD's future water use projections. Water use projections are crucial to safeguard sustainable access to freshwater in the future (Chapter 4). The Water Futures and Solution initiative (WFaS) has developed a set of global water use scenarios consistent with the recent Assessment Report framework of the Intergovernmental Panel on Climate Change (IPCC), notably the Shared Socio-economic Pathways (SSPs). In this step, using two different downscaling techniques, I developed two sets of regional water use scenarios consistent with the WFaS global assessment, based on the national assumptions made for China in the WFaS assessment. With these scenarios, I explored sectorial water use projection for the PRD.

The results of water use projections indicate significant differences in the PRD's regional development trends, compared to China's national scenarios. The regionalized scenarios projected lower water use because of the lower share of PRD's manufacturing sector in total Gross Domestic Product (GDP), and higher rates of technological improvements, compared to national development assumptions. Nevertheless, hydrological challenges remain for the PRD. The total water use of the PRD could still increase by up to 54% in 2030 under the regionalized scenarios.

In the final step, together with YAN Dan, a fellow PhD candidate who worked under the same research project, we explored future water shortage for the Pearl River Basin, and potential contribution of different water allocation strategies to water shortage adaptation (Chapter 5).

For this joint step, I developed three water use scenarios for the whole PRB. Sectorial water use of different sub-basin area was projected under each scenario. Then, the projected water use was confronted with the water availability projected by YAN to assess water shortage in the PRB. Next, four extreme water allocation strategies were defined, prioritizing upstream water use, Pearl River Delta water use, irrigation water use, and manufacturing water use, respectively. The impact of the four strategies on water use and related economic output was assessed against water use and water availability scenarios.

According to the results, almost all the regions in the PRB are likely to face water shortage in the future under the four strategies. The results showed that the increasing water use contributed twice as much as the decreasing water availability to water shortage. None of the water allocation strategies tested was sufficient to solve the water scarcity in the PRB. Moreover, the economic losses differed greatly under the four water allocation strategies. Prioritizing the delta region or manufacturing sector could result in lower economic losses than the other two strategies. This suggests that developing water resources management strategies requires compromise between different water users.

The analysis of the sectorial water use shows that the parameters used in the global assessment needs to be regionalized first based on regional historical records. However, calibration of the regional specified parameters requires well documented (sub)sectorial water use data and corresponding socio-economic data on regional scale, which are not always readily available.

Further, the conceptual framework of water use used in this study also has the ability to obtain monthly fluctuation of water use. This provides possibility to analyse the monthly water balance, and to evaluate different development strategies and their impact on intra-annual events such as salt intrusion induced water shortage during the dry season. This ability makes the conceptual framework a valuable tool to support sustainable water management.

Last but not least, this thesis provides a scientifically sound and feasible method to develop the scenario assumptions for regional assessment of sectorial water use, by linking regional specified historical trends and future development targets with the national assumptions produced in global assessment following SSPs scenarios. The results showed that the method can generate regional water scenarios consistent with global assessment. And the sectorial water use projections based on these scenarios could capture the fluctuation of regional sectorial water use.

The conceptual water use framework and the methods developed in this thesis can generate regional water use scenarios to facilitate future studies in producing consistent and comparable results when assessing regional sectorial water uses. These methods are transferable to other large river basins, especially for the heavily urbanized delta regions, provided that data is available (Chapter 6).

Projection of future water use is crucial to assess the risk of future water scarcity, to develop sustainable management strategies, to safeguard sustainable access to freshwater, and to sustain socio-economic growth in future under changing climate. This thesis provides a step in that direction.

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This thesis is dedicated to my parents, who supported all my curiosity and ingenuousness, unconditionally, with everything they have.

I love them.

Completing a PhD research is hard. So hard. Far beyond my expectation. “One paper per year, how hard could that be?”, I thought. Then, time flew, suddenly, it was already 7 years ago.

Yet, that was truly a beautiful 7 years of my life. A wonderful journey.

On this journey, I travelled many sideways, D-tours, and even U-turns. But on each way, every step, there was always somebody stand by me. While reading these words, you know that was you, my friend, my mentor, my coach, my teammate, my “competitor”. I enjoyed every moment we spend together, on games, sports, trips, parties, and (even) the pure research works of course. There are no words that can possibly express my gratitude and cherishment.

So I look forward.

Completing the PhD is just another start. Ahead, there is still a long way to go. I wish we could create even more beautiful memories on this journey. You know I will always be there.

Love you.

Mingtian

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D I P L O M A

For specialised PhD training

The Netherlands Research School for the
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born on 19 April 1980 in Qinghai, China

has successfully fulfilled all requirements of the
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The SENSE Research School declares that **Mr Yao Mingtian** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 34 EC, including the following activities:

SENSE PhD Courses

- Research in context activity: ‘Co-organizing writing course on communication for a scientific and general public (2016-2017) and writing a press release demonstrating the insights from the writing course’

Other PhD and Advanced MSc Courses

- Career assessment, Wageningen University (2014)
- Entrepreneurship in and outside science, Wageningen University (2015)
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