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Mitigation of China’s Water Scarcity and Water Pollution by Adjusting its Economy and Development Patterns

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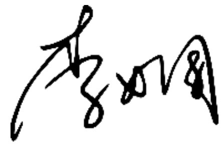

Abstract

Water scarcity and water pollution have constituted great challenges to the world, especially Republic of China (referred as China throughout the whole thesis for simplification), a country constrained by its inadequate water endowment, uneven water distribution, and degraded water quality. Yet current water engineering projects and stringent water regulations are unable to throughout address its water dilemmas, as the interrelationship between water status and economy and development patterns, and the consideration of water footprint or virtual water embodied in commercial trade and supply chains are often neglected when making policies. Hence, this thesis proposes a potential route to alleviate China's water scarcity and water pollution through the adjustment of its economy and development patterns with the ultimate goal of achieving China's water sustainability without stunting its economy and development.

This thesis first explicitly describes the main methods it applies to account China's water scarcity and water pollution across 42 economic sectors at the national and the city levels from production and consumption perspectives, which are the compilation of China's water datasets and the application of Environmentally Extended Input-Output Analysis (EEIOA). Regarding water datasets, four indicators are chosen for compilation, including water withdrawal, water use, ammonia nitrogen (NH_4^+) discharge, and COD discharge. And the application of EEIOA includes Single Regional Environmentally Extended Input-Output Analysis (SREEIOA) and Multi-Regional Environmentally Extended Input-Output Analysis (MREEIOA).

This thesis then conducts four case studies to illustrate how China's water scarcity and water pollution has been negatively and positively affected by its economy and development patterns in small and large scales respectively, and to suggest potential approaches to mitigating China's water scarcity and water pollution by adjusting its economy and development patterns.

Case Study 1 explores the water utilisation in five energy sectors of cities in the Beijing-Tianjin-Hebei (BTH) region, and discusses how synergistic development of the region could facilitate the water utilisation of energy sectors in this region. Water sits at the nexus of energy, and great water supply could guarantee a diverse supply of reliable, affordable and sustainable energy. This case study calculates the 2012 water withdrawn directly for five energy sectors, and total water withdrawal embodied in these energy supply chains by applying city-level SREEIOA. The results suggest that: First, synergistic development could greatly improve water utilisation in electricity in the BTH region. Electricity accounted for 69% (669 Mts/965 Mts) and 72% (8857 Mts/12318 Mts) of the total direct and embodied water withdrawal in five energy sectors respectively, however, this energy sector had low water efficiency, which could be improved by forming a complete supply chain in the region. Second, synergistic development enables each city to optimise its advantageous energy sectors, which promotes the overall water utilisation in the BTH region, such as cities dominated by energy resources excavation (Tangshan and Handan), energy processing (Beijing and Tianjin), or both (Cangzhou). Third, synergistic development encourages well-developed cities to provide technological guidance to the rest of

cities in the BTH region. Of all the cities in the BTH region, Beijing and Tianjin had the largest direct (203 million tonnes (Mts) and 148 Mts) and embodied (6690 Mts and 1476 Mts) water withdrawals in energy sectors and were ranked top in water efficiency (4 x 10^{-4} tonne/CNY and 3 x 10^{-4} tonne/CNY).

Case Study 2 assesses the overall reduction of anthropogenic NH_4^+ discharge attributed by economic progress and development in the Pearl River Basin (PRB). NH_4^+ is a critical pollutant that contributes to eutrophication, and thus research on approaches that trigger changes of NH_4^+ discharge in the PRB can hugely improve the offshore environment. In this case study, 2011 and 2017 NH_4^+ discharge data across industries and economic sectors were compiled and analysed for cities in the PRB. According to the results: first, more attention was paid on NH_4^+ discharge reduction in household, agriculture and industry. The overall reduction of NH_4^+ discharge in the PRB was mainly attributed by household (149.91-86.77 thousand tonnes (Kts)), agriculture (66.55-36.35 Kts) and industry (26.84-15.87 Kts). Second, the Pearl River Delta (PRD) was identified as a critical area in the PRB for the overall NH_4^+ discharge reduction due to its economic dynamics and dense population. With only 8 cities, the PRD accounted for approximately 34% (118.45 Kts/353.23 Kts in 2011; 74.76 Kts/217.86 Kts in 2017) of the total reduction of NH_4^+ discharge in the PRB. Third, awakening civic awareness was the determinant of the reduction of NH_4^+ discharge in household in the PRB as almost all the cities had declined NH_4^+ discharge in household but increased population. Fourth, economic structure transformation and technological improvement also promoted the NH_4^+ discharge reduction of economic sectors (except household). The most significant decreases in NH_4^+ discharge could be seen in cities or their economic sectors with the sharpest decline of NH_4^+ intensities, such as Ganzhou's and Foshan's nonferrous melting, Nanning's chemical product, Foshan's and Shenzhen's textile, and Laibin's agricultural product. Fifth, however, more focuses should be further put on cities with increased anthropogenic NH_4^+ discharge.

Case Study 3 examines the imbalance between China's water stress and its virtual water flows embodied in economic trade in China's 313 cities, and points out the urgent need to introduce economic instruments to alleviate the water imbalance. City, as the basic administrative unit, undertakes great responsibilities for obtaining, distributing, and managing its water resources in the supply chain (Zheng et al., 2019). Therefore, this case study accounts China's city-level virtual water flows across economic sectors for the first time by applying the 2015 MREEIOA. The main findings include: First, it is necessary to introduce economic instruments to ease the water stress of China's regions which were mainly responsible for water export in agriculture and industry. They were Northeast and Northwest (agriculture), East China and Central China (industry). Second, economic instruments need to be introduced to support major water exporters as they tended to suffer from more severe water stress but gained less economic profits. It was seen that water imported by certain cities required rallying support of its surrounding or even cities, especially major water exporters with the most enormous volumes of water outflows but suffered from severe water stress. And these water exporters were often oriented by low value-added but highly water-intensive economic sector agriculture. Third, there were also three types of cities or economic sectors that required the aid of economic instruments to mitigate their water stress: (1) cities that were either highly self-dependent or heavily dependent on the other cities' water supply as they were more likely to confront potential water vulnerability (such as Urumqi, Wuhan, Shanghai); (2) cities had great water investment but gained low economic returns so that their economic carrying capacity were rather low, such as Urumqi. (3) cities/economic sectors that undertook great responsibilities for water export but the responsibilities were in fact beyond their capabilities, such as Maanshan's chemical and metal&nonmetal and Daqing's mining.

Case Study 4 uncovers the positive impacts brought by the shifts in economy and development patterns on national water management. Over the past decades, China has undergone profound social and economic transitions, which evokes urgent needs to quantitively analyse its influences on China's water scarcity and water pollution in the supply chain. Hence, in this case study, national data of water use and chemical oxygen demand (COD) discharge were compiled and then applied in EEIOA to detect the dynamics of China's direct and embodied water across individual economic sectors from 2010 to 2015. It is found that: First, domestic energy policy and economic stimulus optimised the water use and reduced water pollution in key producer (electricity) and consumer (construction) sectors in the virtual water supply chains. Electricity's direct water use declined due to the transition of China's energy structure from coal to renewable energy. Construction's embodied water use and COD discharge skyrocketed (65-92 Bts) as infrastructure construction and real estate could boost the national economy in the post-financial crisis era (Giang & Sui Pheng, 2011). Second, urbanisation alleviated China's water crisis to some extent. Urban consumption occupied the largest percentages (over 30%) of embodied water use and COD discharge, but embodied water intensities in urban consumption were far lower than those in rural consumption. Third, the 'new normal' phase witnessed the optimisation of China's economic/industrial structures and this improved China's water status. Embodied water use in light-manufacturing and tertiary sectors increased while that in heavy-manufacturing sectors (except chemicals and transport equipment) dropped. Fourth, the changes in international situation also provided China some opportunities to optimise its water structure. In the post-financial crisis era, China's water use (116-80 billion tonnes (Bts)) and COD discharge (3.95-2.22 Mts) embodied in export tremendously decreased while its total export values (11-25 trillion Chinese Yuan (CNY)) doubled. Under globalisation and the rise of South-South trade, China started to relocate water use and COD discharge embodied in production activities for low-end sectors, such as textile, to other developing countries, such as textile.

This thesis then summarises the above-mentioned findings obtained from all the case studies. It can be concluded that China's economy and development patterns exert the following negative effects on its water scarcity and water pollution: (1) Economic disparities and development gaps could increase water inequality; (2) Unclear division of labour and unoptimised industrial structure could easily lead to low water efficiency, especially in water-intensive industries/economic sectors; (3) Economic trade without much consideration of virtual water embodied in supply chains could trigger imbalance between water stress, virtual water supply. On the bright side, China’s economy and development patterns also bring the positive effects to its water scarcity and water pollution in the following aspects: (1) The optimisation of economic structure and the fulfillment of industrial transformation could greatly ease water scarcity and water pollution; (2) Economic and social development could also attribute to the mitigation of water scarcity and water pollution. Based on these effects, this thesis then proposes potential approaches to alleviating China’s water scarcity and water pollution by adjusting its economy and development patterns. These measures include: (1) strengthening regional cooperation and encouraging synergistic development; (2) proactively reacting to changes in international situation and making corresponding domestic policy; (3) re-scheduling supply chains and economic trade patterns by introducing the concept of water footprint. To support these measures, this thesis also puts forward some policy recommendations, which include: (1) adjusting water pricing and appropriating water subsidy in less-developed administrative units or in water-intensive /water-polluted industries or economic sectors; (2) introducing water rights trade; (3) adhering to the principles of development economics and circular economy with the ultimate goal of achieving China’s water sustainability.

This thesis makes great contributions to the existing academic field. Theoretically, this thesis makes a breakthrough by conducting China’s city-level water footprint research with the consideration of both water quantity and water quality indicators. This bridges the research gap about limited city-level water footprint studies/water-energy nexus in water footprint studies, and limited water footprint studies related to water quality in the current research filed. This thesis also fills the absence of the existing literature by tracing water pollutants triggered by specific anthropogenic activities of all the cities within a river basin. Methodologically, this thesis compiles a water withdrawal dataset for China’s 313 cities and a NH_4^+ discharge dataset for the PRB’s cities for the very first time. It also applies city-level multi-regional environmentally extended input-output table in China’s water footprint study for the very first time. From the empirical and policy-related perspectives, this thesis chooses representative regions or cities as case studies so that empirical results and policy recommendations could be partly mirrored in other regions or cities at similar development stages.

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PhD Achievements

Published Papers:

Li, X., Shan, Y., Zhang, Z., Yang, L., Meng, J., & Guan, D. (2019) Quantity and quality of China's water from consumption perspectives. *Environmental Research Letters, 14*(12), 124004. https://doi.org/10.1088/1748-9326/ab4e54

Li, X., Yang, L., Zheng, H., Shan, Y., Zhang, Z. Song, M., Cai, B., & Guan, D. (2019) City-level water-energy nexus in Beijing-Tianjin-Hebei region. *Applied Energy, 235,* 827-834. https://doi.org/10.1016/j.apenergy.2018.10.097

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Chapter 1 Introduction

1.1 Water Scarcity and Water Pollution, the Most Critical Global Water Crisis

Water is of paramount importance as the origin of all things. It underpins most aspects of economies and sustainable development (WWAP, 2021). The United Nations incorporates water resources management into Sustainable Development Goal (SDG) in the United Nations (UN)' 2030 Agenda for Sustainable Development (UN, 2021). Even though it is only ranked as SDG 6, water resources management also closely relates to the accomplishment of other SDGs since water sits at the nexus of several issues, such as energy generation, food security, human health, biodiversity in ecosystems.

Despite the significance of water, the global water crisis has become a concerning issue. According to World Economic Forum (WEF), water crisis has been considered as the top 5 global risks by impact in the evolving risks landscape for 10 consecutive years, from 2012 to 2021 (WEF, 2021). Of water crises, water scarcity (water availability and water demand), and water pollution (water quality) are the most critical aspects because unlike water-related extreme events, floods and droughts, they are more likely to be anthropogenic-driven and intervened by humans.

Regarding water scarcity, 1.39 billion cubic kilometres of water covers 75% of earth surface. Still, less than 3% of water can be utilised due to the difficulty to process salty oceanic water or to extract water locked up in various forms such as glaciers, polar ice caps, permanent snow, soil (NASA Earth Observatory, 2010). Even under this circumstance, global freshwater use has at least increased by a factor of seven from 1990-2010, and this upward trend tends to continue (Food and Agriculture Organisation of the United Nations AQUASTAT (FAO AQUASTAT), 2021; Organisation for Economic Co-operation and Development (OECD), 2012). By 2030, the collective demand of humans for water is projected to outstrip foreseen supply by approximately 40 per cent (WEF, 2012). By 2050, over half of the global population will be living in water-stressed areas (WWAP, 2020). For water pollution, the latest statistics show that 785 million global people, 1 in 10, lack access to clean water, and it is reported that water-related disasters account for 70% of all deaths related to natural disasters (United Nations Children's Fund/World Health Organisation (UNICEF/WHO), 2019; World Bank Group (WBG), 2021a).

1.2 China's Water Scarcity and Water Pollution

Water scarcity and water pollution even take a greater toll on China than many other parts of the world. In terms of water scarcity, China accommodates almost 20 per cent of the population in the world, but has only less than 7 % of the world's fresh water, which makes its annual per capita water about one-third of the world average (WBG, 2021b). Of China's 31 mainland provinces (except Macau, Hongkong, Taiwan), 11 has per capita water lower than 1000 m^3, the threshold for the world water poverty mark (National Bureau of Statistics (NBS), 2020; WBG, 2009). China's water scarcity, however, exacerbates by the spatial mismatch of water distribution. The south of China occupies 78% of the nation's available water but only 58% of its population; The north of China solely owns 22% of the nation's available freshwater but 42% of its population (NBS, 2020; Ministry of Water Resources of the People's Republic of China (MWR), 2021). Besides, China's water demand has been continuously increasing, and it was predicted that the gap between its water supply and water demand would reach 24% by 2030 (WEF, 2009). The most recent statistics also indicate that China has unsatisfactory water efficiency, whose water productivity (17.2 United States dollar (USD) per cubic metre of water), the Gross Domestic Product (GDP)-total freshwater withdrawal ratio, is still lower than the world standard (20.6 USD per cubic metre of water) (WBG, 2021b). Concerning water pollution, despite significant water quality improvement over the past years, there is still 16.6% of surface water inferior to Grade III (Environmental Quality Standards for Surface Water GB 3838-2002) and 22% of coastal water unmet Grade I and Grade II (Sea Water Quality Standard GB 3097-1997), which refers to water unfit for human contact due to contamination (China National Environmental Monitoring Centre (CNEMC), 2021).

To make matters worse, China's water scarcity and water pollution interrelate (WAAP, 2017). Water scarcity can trigger the deterioration of water quality. For example, insufficient water impairs a water body's ability to absorb nutrients, which could cause hypoxia and release secondary pollutants, and ultimately render eutrophication, water blooms and red tide. In turn, inadequate water quality exacerbates freshwater scarcity due to the decline of water suitable for human uses (van Vliet et al., 2017). Therefore, there is an urgent need to solve China's water scarcity and water pollution.

In response, China's government has run several water engineering projects, such as the well-known South-to-North Water Diversion and Three Gorges Dam. In the meantime, the government has executed a series of water-related policies, such as the most stringent water management policy 'Three Redlines' that issued in 2011 to regulate water resource development & utilisation, water efficiency, and water pollution (China Science Communication (CSC), 2021a), 'Water Tens' (The Central People's Government of the People's Republic of China (GOV), 2015) which raised ten actions plans for prevention and control of water pollutions, or the 'Blue Water Protection Campaign' that launched during the 13th Five-year Plan (2016-2020) to further fight against the degradation of water quality (GOV, 2018). Yet these countermeasures cannot throughout combat China's water crisis because the alleviation of its water issues is also closely associated with its economy and development patterns.

1.3 China's Water Scarcity and Water Pollution Affected by its Economy and Development Patterns

The importance of studying China's water scarcity and water pollution, especially how it is affected by economy and development patterns, can be highlighted from global and domestic perspectives. For a worldwide view, the importance is threefold: (1) Freshwater and pollutants are transferred naturally via water run-off, and thus China's water crisis has a bond with its adjacent countries. (2) Surrounded by the China Sea (3 million km^2), China's water pollution can be spread to a broader range via ocean currents. (3) In 2016, China overtook the United States as the world's largest exporter, and now its export (2.57 trillion USD) has greatly surpassed that in the United States (1.51 trillion USD) due to its competitive advantages in labour- and water-intensive manufacturing (The Observatory of Economic Complexity (OEC), 2021). The dilemmas lie in that China offers the world economically efficient and desirable products but at the same time entails greater environmental responsibilities than it can bear, and the overall global ecological disruption could have been lessened if these products were made in countries elsewhere with more abundant water resources or more advanced technology (Liu et al., 2016). Before the consensus of sharing environmental responsibilities can be reached among economies (For instance, trade importers pay the additional environmental costs to trade exporters for trade exporters to rehabilitate ecology, such as afforestation to conserve water and soil), China itself undertakes the responsibility to alter this situation without affecting the vitality of its international trade by countermeasures such as adjusting export orientation strategies. The above-mentioned points show that water scarcity and water pollution in China (mainly triggered by China's international trade) is the key to the global water environment.

Regarding a domestic view, China's water scarcity and water pollution could either be positively or adversely affected by its economy and development patterns. As an emerging economy, China's economy has skyrocketed since the 1978 economic reform, and its annual GDP growth rates average 12% (OECD, 2021). China's total population has risen from 542 million to 1.4 billion from 1949 to date (NBS, 1949-2020). Yet the rise of China at this unprecedented rate has also been built upon the rapid expansion of industrialisation and urbanisation at the cost of the aquatic environment (Guan et al., 2014). On the contrary, shifts in the structure of economy may ameliorate the situation, such as reforming traditional water-intensive production activities with the employment of technology. Furthermore, China has established economic zones to promote synergistic development at the regional level, such as 'Three Major Economic Circles' (Yangtze River Delta, Pearl River Delta (PRD), Bohai Rim), and 'Seven Urban Agglomerations' (Jing-Jin-Ji, Yangtze River Delta, the Greater Bay Area, Chengdu-Chongqing, Triangle of Central China, Central Plains, Guanzhong Plain). This economy and development pattern does strengthen regional and inter-regional cooperation with increasing local commercial trade, which offers an opportunity for the optimisation of water utilisation. However, if managed improperly, this pattern might also lead to unfair environmental responsibilities allocation by sacrificing the interest of one to satisfy another (Zheng et al., 2019). To some extent, local economy and development patterns can affect whether China's water scarcity and water pollution would be alleviated or degraded.

1.4 Research Questions and Objectives

This thesis further establishes the link between China's water management with its specific economic activities and development patterns with the attempt to answer the primary research question, "How could economy and development patterns be adjusted to alleviate China's water scarcity and water pollution?". And the following sub-questions are then raised correspondingly:

1. How China's water scarcity and water pollution across economic sectors on different scopes from production and consumption perspectives could be accounted?
2. How the influences of China's economy and development patterns on its water scarcity and water pollution could be measured?
3. What positive and negative effects have economy and development patterns brought to China's water scarcity and water pollution over the past years?
4. What approaches are considered practical and effective to adjusting economy and development patterns to abate China's water scarcity and water pollution?

By addressing these research questions, this thesis aims to unlock the potentials for mitigating China's water scarcity and water pollution through the adjustment of economy and development patterns, and to ultimately facilitate China's water sustainability without stunting its economy and development. The specific objectives are:

To provide clear arguments that where this thesis stands in the existing research filed compared with other studies that discuss the relationship between economy, development and water management, especially empirical work in China, or other research that adopt similar methods (Chapter 3).

To construct a methodological framework to compile water data regarding its quantity and quality across individual economic sectors in different scales, and to account virtual water by applying these data (Chapter 4).

To investigate the adverse effects that one's economy and development patterns might bring to its water scarcity in a certain region, with the case of water utilisation in energy sectors of cities in the Beijing-Tianjin-Hebei (BTH) region (Chapter 6).

To evaluate the positive impacts that one's economy and development patterns might exert on its alleviation of water pollution in a certain region, exemplified by nutrient changes of cities in the Pearl River Basin (PRB) (Chapter 7).

To point out how China's water scarcity has been aggravated by its economy and development patterns at national scope by quantifying virtual water flows embodied in commercial trade among China's main regions and cities (Chapter 8).

To illustrate how China's water scarcity and water pollution have been greatly mitigated due to its shifts in economy and development patterns at the national scope (Chapter 9).

To have in-depth discussions about the empirical results obtained from four individual and discrete case studies (Chapter 6-Chapter 9) by putting their results together and summarising key findings that they have (Chapter 10 and Chapter 11).

To suggest practical approaches to alleviating China's water scarcity and water pollution by adjusting economy and development patterns and to put forward policy recommendations based on China's current institutional and policy landscape (Chapter 5 and Chapter 10).

1.5 Research Outline

This thesis consists of eleven chapters.

Chapter 1 gives a brief introduction of this thesis' background, highlighting the necessity to study China's water scarcity and water pollution, and one of the coping strategies by adjusting its economy and development patterns. This chapter also covers research questions to be addressed, and research objectives to be achieved.

Chapter 2 introduces a frame diagram and walks through the research framework of this thesis. The main purpose of this chapter is to link each individual chapters together and to offer a clearer readership.

Chapter 3 is the literature review of important concepts that underpin this thesis, and of relevant studies that involve both water scarcity and/or water pollution and economy and/or development patterns in the research field, especially water footprint studies and those empirical work in China. This chapter then emphasises research gaps to be filled.

Chapter 4 describes the characteristics and fundamentals of methods applied in this thesis in detail, including the method to compile datasets regarding water quantity and quality across economic sectors at the city and national levels, and the method to account virtual water called Environmentally Extended Input-Output Analysis (EEIOA).

Chapter 5 presents the policy landscape that discusses China's institutional and policy context associated with the relationship between economy, development and water, energy management in order to better contextualise and ground policy recommendations for the following empirical chapters.

Chapter 6 to Chapter 9 constitute the main body of this thesis, which incorporates four case studies about how China's water scarcity and water pollution has been negatively (Chapter 6 and Chapter 8) and positively (Chapter 7 and Chapter 9) affected by its economy and development patterns in relatively small (Chapter 6 and Chapter 7) and large (Chapter 8 and Chapter 9) scales respectively. Chapter 6 examines how synergistic development of the BTH region enables more efficient water utilisation in energy sectors of cities in the region. Chapter 7 analyses the changes of nutrient discharge attributed by the economic transformation of cities in the PRB. Chapter 8 clearly demonstrates how the imbalance between water stress and virtual water flows could be alleviated by economic trade in China's seven regions and 313 cities. Chapter 9 showcases the overall improvement of national water management through the adjustment of economy and development patterns.

Chapter 10 discusses the empirical results from Chapter 6 to Chapter 9. This chapter mainly probes into what positive and negative influences that the changes in economy and development patterns could have on water scarcity and water pollution, and then suggests potential approaches to alleviating water scarcity and water pollution through the adjustment of economy and development patterns as well as corresponding policy recommendations.

Chapter 11, corresponding with Chapter 3, Chapter 4, Chapter 5 and Chapters 6-10, summarises this thesis's key findings and its contribution and innovation, and puts forward policy recommendations.

Chapter 2 Research Framework

This thesis formulates analytical frameworks that take a view of the influences of China's economy and development patterns on its water scarcity and pollution. This chapter unfolds this thesis' research framework by constructing a frame diagram. Figure 2-1 presents a frame diagram that showcases the overall framework of this thesis.

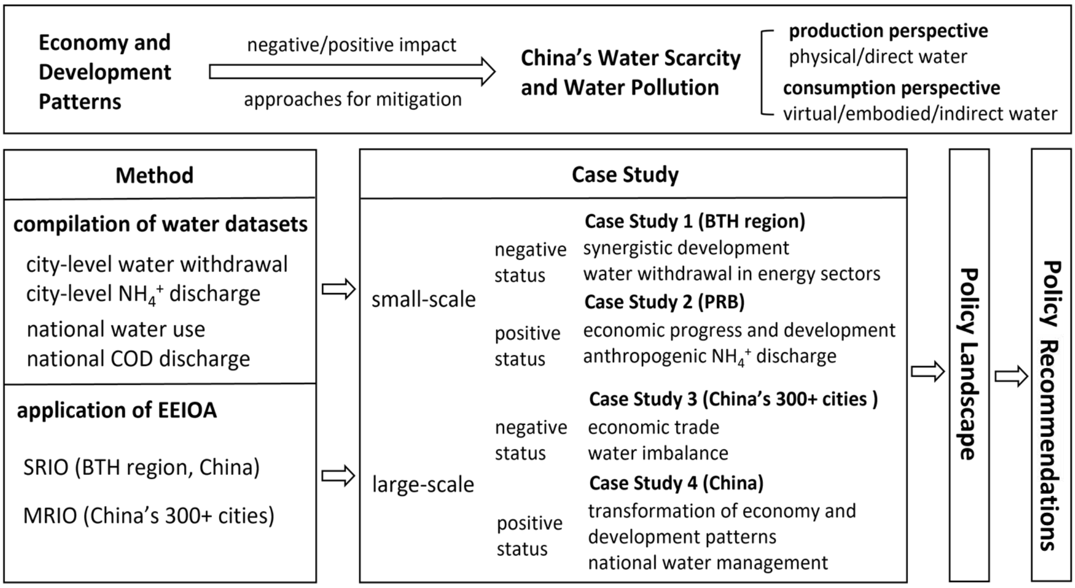

Figure 2- 1: The overall framework of this thesis

On the top of this frame diagram, it reflects the main theme of this thesis, how economy and development patterns could be adjusted to alleviate China's water scarcity and water pollution. The main theme lays a foundation for the whole thesis, which guides research questions and objectives (Section 1.4) and affects the other aspects such as methods adopted, case studies chosen. In order to better explore the main theme, this thesis first investigates what possible negative and positive impacts could be brought by the changes of economy and development patterns on China' water scarcity and water pollution. Then based on these potential impacts, this thesis then suggests approaches to mitigating China's water scarcity and water pollution through the adjustment of its economy and development patterns. However, it is worth noticing that this thesis looks at China's water scarcity and water pollution issues from both production and consumption perspectives. The production perspective examines only physical/direct water while the consumption perspective focuses on virtual/embodied/indirect water, and these concepts will be clearly elaborated in Section 3.1.

The left column at the bottom of this frame diagram identifies methods adopted in this thesis, which is the premise for the applications of the following case studies. The methods incorporate two parts: one is the compilation of water datasets, and the other is the application of economic models that consider these water data as inputs. These water datasets not only correspond to the economic models, but also to research scopes in the following case studies. They are water datasets for city-level water withdrawal (Section 4.1.1 and Case Study 1, Case Study 3), city-level ammonia nitrogen (NH_4^+) discharge (Section 4.1.2 and Case Study 2), national water use and national COD discharge (Section 4.1.3 and Case Study 4). The economic models applied are called EEIOA, and they include SRIO (Single-Regional Environmentally Extended Input-Output Analysis) and MRIO (Multi-Regional Environmentally Extended Input-Output Analysis). The methodology for SRIO and MRIO will be depicted in Section 4.2.1 and Section 4.2.2 respectively, and empirical studies that apply for SRIO are Case Study 1 (a single region, BTH region) and Case Study 4 (a single country, China) while empirical research which adopts MRIO is Case Study 3 (multiple cities, China's 313 cities).

On the basis of the main theme and the methods, this thesis then conducts four case studies. As mentioned earlier, four typical case studies are chosen according to two main dimensions: research scale (small-scale, mainly targeting at cities in a specific region, or large-scale, mainly covering the whole country or all the cities in the country) and the influences of economy and development patterns on water scarcity and water pollution (positive influences or negative influences). Case Study 1 and Case study 2 focus on small-scaled research areas, the BTH region and the PRB respectively, while Case Study 3 and Case Study 4 concentrate on large-scaled research areas, China and its 313 cities. And according to empirical results, Case Study 1 and Case Study 3 mainly probe into negative effects brought by economy and development patterns on local water scarcity and water pollution. Case Study 1 (Chapter 6) points out negative status of water withdrawal in energy sectors in the BTH region. Case Study 3 (Chapter 8) analyses China's water imbalance between water stress and virtual water flows embodied in economic trade among China's 313 cities. On the contrary, Case Study 2 and Case Study 4 mainly examine positive effects exerted by economy and development patterns on water scarcity and water pollution. Case Study 2 (Chapter 7) illustrates how the overall reduction of anthropogenic NH_4^+ discharge in the PRB was greatly attributed by local economic progress and societal development. Case Study 4 (Chapter 9) points out how the overall improvement of national water management benefited from the transformation of economy and development patterns.

According to the empirical results obtained from four case studies and discussions towards these case studies (Chapter 10), this thesis not only proposes potential approaches to alleviating China's water scarcity and water pollution through the adjustment of its economy and development patterns, but also has some policy recommendations (Chapter 11) as an expansion on these potential approaches. Before policy recommendations are proposed, however, this thesis also has a separate Chapter for policy landscape (Chapter 5) to evaluate China's current economic or social policy closely associated with water management and to ground evidences for the recommended policy in this thesis.

Chapter 3 Literature Review

To better locate this thesis within the current research field, the literature review starts with the introduction of the core concepts in this thesis, especially water footprint. It then discusses the relationship between economy, development and water management and compares water footprint studies with another types of research regarding this relationship, mainly from the perspectives of content and methods. Finally, it highlights empirical work related to China's water footprint and identifies research gaps.

3.1 Water Footprint and its Development

Water footprint is an important concept contributing greatly to the academic field that strengthens the understanding of intricated relationship between economy, development and water resources. Water footprint uncovers the influences of trade and commodity production or consumption on water resources (Hoekstra and Chapagain, 2008). Most importantly, water footprint is able to examine both factors in an integrated supply chain, instead of solely looking at them independently and separately. In addition, water footprint shows strong spatiotemporal characteristics so that it can be clearly seen how water is appropriated for human purposes for a certain period of time in a specific area (Hoekstra et al., 2011). This can form a good basis for local water assessment and local water strategies, such as saving local water resources or reducing its dependency on external water suppliers. By talking about water footprint, the discussion about sustainable and equitable water allocation and water use on a board scale could be fed and water sustainability could be ultimately achieved. As water impacts in one place cannot be offset simply by water saving in another places like carbon emissions (Chapagain and Orr, 2008), water footprint assessment would greatly encourage the collaboration of stakeholders in different geographical areas.

To better understand the water footprint, its development should be traced. The concept of water footprint was formed on the basis of virtual water and ecological footprint. Virtual water, also known as embedded or embodied water, was brought up by Tony Allan in 1993 (Allan, 1993), and the concept defines the volume of water used in reality to produce a product, including water use of all raw materials for the end product. In 1996, ecological footprint was raised by Wackernagel and Rees, and it measures how much land a human population requires to produce the resources it consumes and to absorb its wastes (Rees, 1992, Wackernagel and Rees, 1996). Water footprint was then developed as an analogue to the ecological footprint, but water footprint directly targets at the whole freshwater ecosystem. By combing the concepts of virtual water and ecological footprint, Arjen Hoekstra coined the concept of water footprint by widening the application of virtual water in 2002 (Hoekstra, 2003). Water footprint considers not only physical/direct water (production perspective) but also virtual/indirect water over the full supply chain (consumption perspective), where virtual water is re-defined as the total volume of freshwater consumed or polluted for the production of goods and services by the consumer (Hoekstra et al., 2011).

For comprehensive water footprint studies, four procedures should be followed, as instructed by Hoekstra et al (2011). The goals and scopes of water footprint studies should first be clearly identified. The second step is conducting water footprint accounting. Then water footprint sustainability is assessed and corresponding response strategies could be formed.

Despite the fact that water footprint is a useful analytical tool for water management, its challenges and limitations still exist. To start with, water footprint mainly focuses on freshwater resources and their interaction with economic and social factors triggered by specific human activities (production and consumption, social development), and is unable to address certain challenges related to economic, social or even environmental themes in a broader context, such as poverty and climate change.

Meanwhile, water footprint is a multidimensional concept that considers various perspectives and involves different stakeholders (see Table 1). Given the importance of accumulative effects of all types of activities, scopes and indicators should be chosen wisely before conducting water footprint studies.

Table 3-1: Multi-dimensions for Considerations in Water Footprint

Dimensions	Specific Categories			
The Choices of Water Quantity Indicators	**Water use** takes two forms, water withdrawal and water consumption.	**Water withdrawal** is water diverted or withdrawn from a surface water or groundwater source (Vickers, 2001).	**Water consumption** refers to the portion of water which is not returned to its original watershed after its withdrawal (McMahon & Price, 2011).	
The Choices of Water Quality Indicators	**Water pollutants** cover different sources of contamination, including but are not limited to COD discharge and NH_4^+ discharge.	**COD discharge** is an important parameter for indirectly determining the amount of organic pollution in aquatic systems (Islam et al., 2019).	**NH_4^+ discharge** consists of ionised ammonia (NH_4^+-N) and unionised ammonia (NH_3-N), and it is the most ubiquitous form in wastewater and sewage (Constable et al., 2003).	
Water Footprint Components	**Water footprint** could be accounted as a whole without specific divisions.	**Blue water footprint** accounts fresh surface or groundwater.	**Green water footprint** accounts water stored in soil or on top of soil and vegetation.	**Gray water footprint** accounts freshwater required to assimilate pollutants.
Targets of Supply Chain in Water Footprint	Focuses could be placed on **the overall supply chain**.	Focuses could be placed on **the production side**, including **certain processes** or **products** in the supply chain.	Focuses could be placed on **the consumption side**, including **certain consumers** or **a group of consumers**.	
Research Areas	Water footprint could be conducted in **administrative units**, such as **nations**, **municipalities/provinces**, **cities,** or **certain regions**.	Water footprint could be conducted in **river basins** or **catchment areas**.	Water footprint could be conducted in **businesses** or **companies**.	
Other Dimensions	The concept of water footprint could be broadly extended and named in accordance with water indicators chosen, such as **wastewater footprint** and **eutrophication footprint**.			

Source: The dimensions and the concepts for water footprint components are based on theories raised by Hoekstra et al. (2011).

Geographically, for water footprint studies conducted in administrative units (research areas in Table 1), they originally emerge at a global scale, but more understandings would be added to the existing field if they cover more specific geographical areas. However, the smaller an administrative unit is, the larger the external fraction of the water footprint in the area will be. Thereby, one of the major questions becomes how to deal with the lack of required data, especially in a small administrative unit.

3.2 Water-Energy Nexus in Water Footprint

In this thesis, the concept of water-energy nexus also appears in empirical work, as a component in water footprint. It is crucial that water-energy nexus is considered in water footprint studies. Water and energy are inextricably interlinked. Water is required in a series of energy production processes, such as raw materials extraction and processing, electricity production, thermal plant cooling, waste products treatments and energy-generation facilities maintenance. On the other hand, energy plays an essential part in water-related processes such as desalination of brackish water or seawater, pumping from groundwater aquifers, water transfer from water-rich to water-poor regions, water purification and wastewater treatment (Gleick, 1994). If the quality, quantity and accessibility of water is declining, the promotion of a diverse supply of reliable, affordable and sustainable energy will be at stake (Rio Carrillo and Frei, 2009). Conversely, restricted energy capacities limit the ability to produce clean water (Gleick, 1994). Hence, water-energy nexus studies could greatly promote the sustainability of both water and energy resources, and to some extent help reduce the negative impacts exerted on water and energy systems by natural disasters, such as hydropower shortfalls caused by heat wave, or decreases in power output due to droughts.

When Gleick (1994) first introduced the water-energy nexus, this concept only refers to water or energy used for water-related energy processes and energy-related water processes (that is, water or energy used for processes whose main output is energy or water), but neglects ‘water and energy for other purposes’ such as end-use demands and commodities (Kyle et al., 2016). In the later stage, water and energy are then categorised interdependency into production links and consumption links, demonstrating the flow sequence from the environment to the end users (Hamiche et al., 2016). The most typical example is that many researchers started to detect the interaction of virtual water and energy resources in an economy from production and consumption perspectives after the introduction of water and energy footprints. Nevertheless, water-energy nexus in water footprint was more preferred. The reason lies in the fact that broader research targets could be covered with considerations of virtual water flows in multiple energy sectors, including coal mining (coal), petroleum and natural gas extraction (extraction), coking (petroleum refining and coking), production and supply of gas (gas), and production and supply of electricity and heat (electricity). In comparison, water-energy nexus in energy footprint could only explore virtual energy flows in a single water sector, that is production and supply of water.

The introduction of water-energy nexus in water footprint enables researchers to reflect the co-benefits and trade-offs between water resources and energy development in a complete supply chain so that their coordination could be further optimised by the transformation of water use structures or by the re-orientations in energy industry on the basis of quantitative analyses. This brings an enormous advancement to the research field when compared with traditional studies, where researchers were inclined to optimise water resources in energy sectors from the perspective of social science by proposing water and energy policies, such as adjusting water or energy taxes (Zhou et al., 2018), or from the perspective of environmental engineering by advancing technology to improve water or energy efficiency (Qin et al., 2015).

3.3 Relationship between Economy, Development and Water Management

3.3.1 Economy, Development and Water Resources

Economy, development and water management interact with each other. According to Gleick (1993), there are four common approaches of how economy and development exert impacts on water resources: The most obvious approach that economy and development principally affect water flows is direct diversions of water from a variety of water sources, such as rivers and aquifers. The most prominent examples are water intakes for agricultural, industrial and municipal water use. Indirectly, economy and development might affect the hydrological cycle as a result of some water projects (such as reservoirs construction, channel excavation and damming), or alter the water balance by influencing the surface of drainage basins (mainly triggered by urbanisation and agrotechnical measures). From a broader perspective, climate change on global and regional scales caused by economy and development is also likely to affect water flows, hydrological cycle and water balance, especially effects on evaporation and precipitation.

On the contrary, water resource could be a bottleneck to economic growth and social development under some conditions (Howe, 1976). This phenomenon might occur when water supplies are fixed or hard to be expanded for some important production processes where water inputs are fixed in relation to outputs. Under this circumstance, however, water resources could usually be substituted by other inputs, such as the substitution of capital for water by introducing high-technology or transforming the existing production patterns with focuses shifted to less water-intensive products. Besides, with the evolution of economy and development patterns, the reduction in the importance of primary industry and the increase in the significance of secondary and tertiary industries will appear even though water supplies are rigidly allocated among water users over time. Confronting with this evolution, the inability to relocate water resources could force new source development or preclude further growth. Besides, for some impoverished places where water is a controlling factor to human health, the impaired labour productivity would also inhibit their economic and social growth.

Thus, it is essential to probe into the association between economy, development and water management. Water resource development and management remain at the heart of the struggle of growth and they enable responsible economic/social growth (Grey and Sadoff, 2006). On the contrary, the dynamics of water are highly dependent upon economic circumstances and development trajectory. By understanding the nexus of economy, development and water management during a certain period of time, a more diversified, mor efficient and more water-resilient economic structure could then be constructed. Once the virtuous circle phenomenon is formed, the overall economies could no longer easily suffer from water vulnerabilities. In a long-run, the economic benefits will outweigh its investment costs with increasing production and productivity.

In the current academia field, nevertheless, research about economic and societal effects brought by water resources is often straightforward and only requires simple statistical analysis, such as the impact of water scarcity and/or water pollution on the loss and gain of economic surplus (Dolan et al., 2021) and on employment issues (Roobavannan et al., 2017). Comparatively, studies about the water influences exerted by economy and development are more diverse. Therefore, more concentrations should be placed on how economy and development contribute to water dynamics.

3.3.2 Water Footprint Studies and Another Research about the Relationship between Economy, Development and Water Management

In this section, explanations are given about why water footprint is preferred when investigating the relationship between economy, development and water management. To highlight the advantages of water footprint studies, comparisons between water footprint studies and other research with the same topic are made from the perspectives of both content and methods. Combing the perspectives of Friesen et al. (2017), the existing studies are categorised into the following types.

- **The Effects on Water Resources Brought by Specific Anthropogenic Activities, and Statistical Models**

Studies that fall into this category emphasise the effects on water issues in socio-economy or ecosystems triggered by specific anthropogenic activities. Anthropogenic activities usually refer to activities sensitive to external factors such as climate change, or specific activities that could alter water status in a long run such as those associated with policy administration and management.

Anthropogenic activities sensitive to external factors are mostly related to agriculture, as these activities could be highly dependent on factors which vary from year to year such as precipitation. Even without the long-term investigation, relevant studies could be meaningful as case studies. For example, Guyennon et al. (2016) investigated the effect of irrigation on water supply systems and pointed out that irrigation primarily affected groundwater recharge in Apulia region, South Italy. They contribute to the filed as agriculture is by far the largest users of water, especially in development countries.

Anthropogenic activities that alter water status in a long term are normally activities that could be intervened by policy makers or managers, such as urban planning and land management. These studies could to some extent guide future policy orientations. For instance, Guo et al. (2021) set different land management scenarios for China's Jianghuai economic zone and analysed how they would impact on water-related ecosystem services, such as water yield and water purification.

This type of research clearly discerns specific anthropogenic effects to water status. But research in this category could only target at very specific problems to be addressed and has a relatively narrow research scope. And the biggest concern is that result analysis could be one-sided if only limited activities are considered, without taking into account the interactions of multiple elements in the water network.

Moreover, statistical models are often applied for this type of research, especially regression analysis and decomposition analysis. For example, Li et al. (2020) explored the relations between water scarcity and urbanisation by constructing a multi-linear regression model with stepwise regression method. S. Zhang et al. (2018) employed Logarithmic Mean Divisa Index (LMDI) model and identified crop-planting scale and cropping patterns as the influential factors of agricultural water-saving. Nevertheless, statistical analysis is constrained by several aspects, such as the limitations of mathematical knowledge, unverified assumption in both statistical techniques and descriptive interpretations of statistical models, and problems in computer-based calculations (Jeon, 2015; Xie, 2011).

- **Impact of Anthropogenic Factors on Water Pollution in River Basins, System Dynamics Model and Watershed Models**

In this category, studies aim to establish connection between economy, development and water resources by tracing contaminants caused by anthropogenic activities in river basins. The biggest contribution of this type of research is that they depict the trajectory of pollutants from terrestrial areas to river systems. However, only water quality indicators can be investigated.

A part of scholars simulates the trajectory process with System Dynamics (SD) model. SD was created by Jay Forrester in the 1950s and is an approach to understand the nonlinear links of multiple components in a complex economy-society-water system (Forrester, 1971). For example, Xu et al. (2017) examined how different farmers' production decisions affected nitrogen and phosphorous input loads to a river. Yet the complexities of SD render it difficult to identify the sequence of cause-and-effect relationships that constitute feedback interactions without omitting factors that should have been taken into account (Elsawah et al., 2017).

For these studies, watershed models are mostly applied instead. There are multiple watershed models such as SPARROW (Spatially Referenced Regressions on Watershed attributes), Global NEWS (Global Nutrient Export from Watershed Model), SWAT (Soil and Water Assessment Tool), GWLF (Generalised Watershed Functions), AnnAGNPS. DLEM 2.0 (Dynamic Land Ecosystem Model 2.0), as a relatively sophisticated model, even considers key biochemical processes of pollution substances such as nitrogen absorption, nitrification (Yang et al., 2015). Compared with SD, watershed models can more accurately quantify the impact of anthropogenic factors to water pollution in river basins. For example, Robertson and Saad (2011) developed SPARRPW to estimate loads and anthropogenic sources of phosphorus and nitrogen from the Laurentian Great Lakes, and the results indicated that non-point sources contributed to 33-44% of the phosphorous and 33-58% of the nitrogen, while point sources attributed to 14-44% of the phosphorous and 13-34% of the nitrogen. Li et al. (2017) applied Global NEWS to quantify the trajectory of nutrients from land to Beijiang, a tributary of Zhujiang river basin, and the quantitative results indicated that DIN (Dissolved Inorganic Nitrogen) in the river basin was mainly attributed by the application of chemical fertilisation while DIP (Dissolved Inorganic Phosphorous) was contributed not only by chemical fertilisation but also by aquaculture wastewater. Nonetheless, watershed models are integrated models but the natures of territorial source data (yearly/monthly data) and water pollutants data in river basins (daily data) differ. It determines that some data calibration must be involved and only the effects of general aspects in economy and development, rather than the effects of specific anthropogenic activities or specific economic sectors, on water issues in river basins could be probed into. Besides, it is unlikely to trace anthropogenic factors in certain administrative units on water pollution in river basins with watershed models.

- **Long-Term Trend Between Economy, Development and Water Resources, and Decoupling Models**

This type of research focused more on the trends of water and economy, development and their synergies by investigating the long-term relationships between water resources and economy, development, and suggestions towards the coordination of economy and development are often given at the end to better execute water management.

And economy and development can be specially targeted, and most commonly at marine/blue economy, where marine/blue economy refers to economic growth points driven by activities such as fisheries and aquaculture, maritime transportation and sea borne trade, and coastal tourism. This is because that the hydrosphere as it is proved to have a strong link with water pollution and water resource development (Lee et al., 2021). However, this type of research's study places could only be limited to coastal areas. For example, Chen et al. (2017) analysed the decoupling relationship between marine economic growth and marine pollution in China from 2002 to 2013, and an inverted N-shaped relation was shown during the period.

Studies fall into this category could also analyse the relationship between the overall economy, development and water issues. In this case, the most common socioeconomic indicators were considered such as GDP, per capita income, regional industrial structure, CPI (Consumer Price Index), urbanisation rate to represent economy and development status. For instance, Msongaleli et al. (2022) characterised the relationship between urban sprawl and water demand in Dodoma urban district in Tanzania from 1992 to 2029, and the findings revealed that they presented a positive but complex and non-linear relationship. He et al. (2014) observed the relationships between fifteen human activities and long-term coastal environment and found that economic growth of seaside cities had been the main cause of accelerating China’s coastal degradation since the 1950s. Nevertheless, this type of research can only simply observe and predict the overall trends of economy, development and water factors respectively, rather than treating them as a whole. Besides, it is unlikely to study multiple indicators for different study areas simultaneously so that individual case studies could only be analysed separately.

The weakness of this research category is also manifested the methods they apply, mainly decoupling models. Decoupling models are inclined to have the flaw of being too straightforward. Here, Environmental Kuznets Curve (EKC) and Tapio Decoupling Model are taken as examples.

EKC was extended from the Kuznets Curve by Gene Grossman and Paul Krueger (Grossman and Krueger, 1991) and was widely applied to study the relationship between economic growth and water issues. However, their relationships have limited forms, such as N-shaped, U-shaped, or inverted U-shaped curves. And it has been criticised that the types of EKC highly depend on choices of study area, indicators, dataset and statistical technique (Katz, 2015; Rashid Gill et al., 2018).

Tapio decoupling model has become the most widely used eco-economic decoupling model since OECD first introduced the concept (OECD, 2002). Tapio decoupling model was then developed from OECD decoupling model by subdividing the decoupling state into eight states (Figure 3-1) according to decoupling elasticity and calculating the sensitivity of incremental values (Tapio, 2005). Yet it can be seen that Tapio decoupling model can only uncover eight decoupling states, and this model solely requires data in two time periods, so different chosen time periods would add to the uncertainty (Anser et al., 2020).

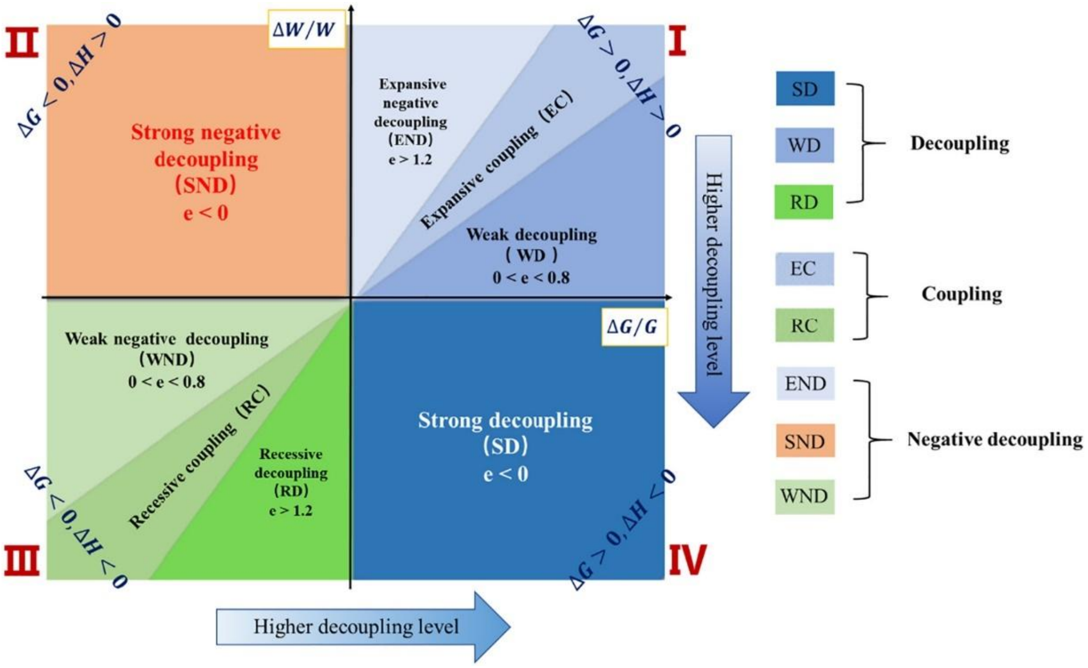

Figure 3-1: Schematic of the decoupling judgment based on Tapio. ΔG and ΔH denote the change in economic growth and water consumption respectively, ΔG/ΔG represents the economic growth rate, ΔW/ΔW indicates the growth rate of water consumption, e is the decoupling index calculated as ΔW/ΔW divided ΔG/ΔG. Source: Wang and Wang (2020).

- **Systematic Frameworks that Balance Economy, Development and Water Resources, and Hydro-economic Accounting Tools**

This type of research constructs systematic frameworks to balance economy, development and water management, planning of water resources. The systematic frameworks are often built on environmental-economic accounting tools, especially hydro-economic accounting tools. And this kind of research has the advantages of proposing optimal allocation strategy regarding economy and development according to water distribution by identifying economic and societal vulnerabilities sensitive to water status and mitigating economic and other losses attributed by water issues. In the existing research field, there are several accounting tools that have been developed. To exemplify a few, Eamen et al. (2021) developed MODSIM-DSS, which simulated interactions between available water resources and demands, and quantified optimal water supply to various economic sectors under different conditions. Reimer et al. (2020) designed a multi-disciplinary design optimisation framework called WEST (Water Economy Simulation Tool) and investigated how economic growth and jobs interacted with surface and groundwater use in case that economic vitality and jobs conflicted with environmental vulnerabilities. Pires et al. (2017) created a comprehensive evaluation system by identifying over 100 water indicators and assessing whether these indicators fulfilled sustainability criteria, including social, economic and institutional criteria. Pedro-Monzonís et al. (2016) applied SEEAW (System of Environmental-Economic Accounting for Water), a tool issued by United Nations Statistics Division, to directly link economic information with water use and water service costs.

However, demonstration and the accomplishment of these hydro-economic accounting tools normally require high data demands, that is, the data disaggregation into small gridded-date. The main reason lies in that those hydrological and economic factors cannot be easily matched. Socioeconomic factors are normally at spatial (administrative regions) and temporal (a year or month) scales, while hydrological indicators are inclined to be an instantaneous value.

- **Water Footprint Studies, and Its Accounting Approaches**

It can be observed that not only the-above mentioned categories have their respective shortcomings in research methods, these studies either constrain themselves to specific research topics, or neglect several details in pursuit of boarder research scopes and longer study periods. Mostly importantly, none of the above studies establishes the links of economy, development and water resources from the perspectives of supply chains, or production and consumption. Under these circumstances, the fifth category should be paid most attention, which is the previously mentioned concept called water footprint. Water footprint studies only started to gain wider exposure in the academic filed in the past decades, later than research fields in the other categories. But these studies did contribute greatly to water quantity and water quality management in global supply chains by identifying the potential water-savers/significant water polluters and proposing corresponding coping strategies. For example, Hamilton et al. (2018) quantified global freshwater eutrophication footprint and global marine eutrophication footprint across 44 countries and 5 rest-of-world regions over the period of 2000-2011, and it was found that clothing, goods for shelter, services and other manufactured products accounted for over 30% of the global freshwater and marine eutrophication footprints. Mekonnen and Gerbens-Leenes (2020a) quantified the blue water footprint of global food production and pointed out that shifting diets to food items with lower water requirement and food waste reduction could improve the water sustainability.

Water footprint accounting approach is a relatively comprehensive method that can reflect the implications of water scarcity and water pollution affected by economy and development, especially by international or domestic trade transactions in the supply chain driven by different final demands. There are two water footprint accounting approaches. One of them is bottom-up approach, such as Life Cycle Assessment (LCA) and Water Footprint Network (WFN). For instance, Crocella et al. (2022) quantified water footprint for traditional crops and highlighted olives presented the highest value of the water footprint and grapes were most likely to be affected by climate change. Okadera et al. (2014) adopted bottom-up approach and found that water footprint of energy production and supply in Thailand for 2010 was nine times greater than that for 1986. However, many studies that applied bottom-up approaches were solely concentrated on agricultural and forestry-based production and energy production (WFN), or specific industrial products (LCA) (Wang et al., 2021). Comparatively, the top-down approach (EEIOA) was extended by Wassily Leontief in 1970 from his economic Input-output framework developed in the late 1930s (Leontief, 1936; Leontief, 1970). And it has the advantage of tracing virtual water in the entire supply chain among individual economic sectors (Feng et al., 2011).

By comparing the existing studies that discuss the relationship between economy, development and water management, it can be concluded that water footprint studies, especially EEIOA, are capable of examining this relationship in a more comprehensive way than other types of research with broader research scope as well as more specific details that analyse the trend of this relationship over time. Therefore, water footprint studies and EEIOA were deployed as the primary research orientation/quantitative method in this thesis in order to better understand the relationship between China's economy, development and water management.

3.4 Water Footprint and China's Empirical Work

China's water footprint constitutes an important part for both global and domestic water resources management. From the international perspective, China was the leading net importer in intermediate trade of virtual water, and the leading net exporter in final trade of virtual water (Wu et al., 2019). Within China, Zhao et al. (2015) clearly pointed out that in China, physical water flows by water transfer projects only took up 4.5% of the national water supply, while virtual water flows accounted for 35% of the national water supply. It was also projected that virtual water trading within China would soar by 2100 (Graham et al., 2020). Hence, China's water footprint plays a vital role in revealing how its water status is affected by its economy and development patterns. In this section, therefore, the empirical work specifically in China will be illustrated in detail, including China's water footprint studies (including water-energy nexus in water footprint) with different scopes and focuses, along with the review for the feasibility of the EEIOA application for China's water footprint studies.

3.4.1 China's Administrative Units and its Water Footprint Studies at Different Scopes

China's administrative units should be first clearly defined to avoid misconceptions before further discussions. China has 34 provincial districts (written as 'provinces' throughout this thesis for simplicity), including 23 provinces, 5 autonomous regions (Inner Mongolia, Guangxi, Tibet, Ningxia, Xinjiang), 4 provincial-level municipalities (Beijing, Tianjin, Shanghai, Chongqing), and 2 special administrative zones (Hongkong, Macau). In total, China owns 333 prefectural districts (written as 'cities' throughout this thesis for simplicity), including 293 cities (including provincial-level municipalities), 30 autonomous prefectures, 7 prefectures, and 3 leagues. Throughout this thesis, 'city' refers to the administrative term that includes urban and rural areas within its administrative border (Zheng et al., 2019).

China's water footprint studies have often been conducted at the national scope. This type of research can focus solely on the domestic water situation by analysing overall trends and structures of water footprint and paying great attention to driving forces that trigger the changes of water footprint from the perspective of different final demands. For instance, Fan et al. (2019) calculated China's water footprint for 10 consecutive years (2002-2012) and identified inhibition effects and promotion factors of water footprint and their changes over time. P. Zhang et al. (2020) evaluated the water use implications of the changes in China’s economic development patterns and urbanisation process during 2002-2017 and suggested that actions such as improving the production efficiency of economic sectors with large consumption-based water use would be the key to offsetting the increase in water use. This kind of studies can also concentrate on the role that China plays in the global supply and demand chain, and how China interacts with other countries in terms of virtual water trade. For example, Wang and Ge (2020) studied China’s water footprint from 1990 to 2010 and clarified China’s main net export destination (developed areas such as North America and Europe) and net importer sources (developing areas such as Africa and Southeast Asia) of its water-intensive products (mainly from agriculture, fishery and light industry). W. Chen et al. (2018) adopted EEIOA to track virtual water flows in China’s foreign trade, and found that virtual water was mainly exported by textile & garment, production equipment to developed countries, while the import of virtual water was mainly from agriculture, and petrochemical produced by emerging economies and resource-oriented countries. However, these studies seldom linked water footprint with international and China’s policy orientations, and thus the analyses were mostly results-driven and lacked convincing support.

China’s water footprint studies have also been investigated at the provincial level. In comparison with previously mentioned national-level studies, this type of research can also probe into the drivers of changes in water footprint, but the nature of this kind of studies determines that they concentrate more on the interactions of economic sectors in China’s regions/provinces and neglect China’s connection with other countries with the ultimate goal to optimise water structures in the domestic supply and demand chain by adjusting economy and development patterns. For example, Cai et al. (2019) evaluated interprovincial water footprint in China during 2002-2012 and found that the water-scarce Northwest and Northeast regions increased virtual water export to the water-rich provinces in Southern China. Xiong et al. (2020) analysed the transitions in spatial distribution and structure of China’s water footprint from 2007 to 2012. The results indicated that the discrepancy of water footprints in northern and southern provinces dramatically enlarged during the study period, and the north also showed a wider urban-rural gap in per capita water footprint than did the south. Zhang et al. (2019) quantified blue water footprint among China’s provinces for the years 2007-2010 and the provincial water footprint variations were found to be affected mostly by per capita GDP, total water resources, per capita water resources, and urban population.

Comparatively, a few studies have focused on water footprint at city level, and they solely include a few cities, or cities in well-known regions. X. Zhang et al. (2020) evaluated the vulnerability of urban water resource networks for China’s six megacities i.e. Beijing, Tianjin, Shanghai, Chongqing, Guangzhou and Shenzhen. The results showed that the large share of external blue water footprint helped Beijing, Tianjin and Shanghai decrease their total vulnerability by 39%, 33% and 28% respectively, but increase their vulnerability to external water shortages.
D. Zhao et al. (2017) quantified water footprint of Jing-Jin-Ji region in 2010, and proposed several strategies to reduce the pressure on this region’s water resources, such as ‘virtual water strategy’ that considered financial compensation from Beijing

and Tianjin to cities in Hebei, reducing the dependency of Hebei's cities' export of water intensive and low value added agricultural products, and the BTH integration strategy that drove the transfer of enterprises with low water utilisation efficiency and heavy pollution. By far, however, China's city-level water footprint studies have not yet been fully understood, especially those cover China's all the cities.

The same situation occurs for water-energy nexus in China's water footprint studies. Studies of water-energy nexus in China's water footprint are also conducted at different scopes. There are several studies have been conducted at the national, regional and provincial levels. For example, Long et al. (2022) traced the energy-water-greenhouse gas nexus in China's national supply chains that included 149 economic sectors, and indicated that the top 30 supply chain paths contributed to 34.99% of energy consumption, to 39.18% of water consumption, and to 40.18% of greenhouse gas emissions in 2017. Tian et al. (2022) explored the relation between water utilisation, energy consumption, and carbon emission of China and the results showed that economic sectors with higher consumption coefficients dominated the transfer of virtual water-energy-carbon. Sun et al. (2018) evaluated the 2012 water footprint of energy supply in Shaanxi province and found that reducing irrigation water was of benefit for both water saving and energy conservation in the agricultural sector.

Similarly, research about water-energy nexus in China's water footprint studies is relatively limited and most of it has only focused on one specific city rather than multiple cities. For instance, Feng and Chen (2017) detected the synergetic effects of water and energy consumption in Beijing and identified real estate as the most important water-energy nexus node under rapid urbanisation. Chen and Chen (2016) synthesised the interwoven connections between water use and energy consumption in Beijing and found that the recycling rates in water networks (22-23%) were lower than those of energy networks (28-29%).

3.4.2 China's Water Footprint Studies regarding Water Quantity and Water Quality
Many researchers who study China's water footprint have laid importance on water quantity or water scarcity. W. Zhang et al. (2020) evaluated virtual water flow risks in Northeast China and identified Xinjiang, Jiangsu, Anhui and Hebei province as the main split provinces to Northeast China. Yu and Ding (2021) quantified water footprint in Beijing, and it was found that Beijing's water footprint decreased from 1.89×10^{10} m^3 in 2007 to 1.61×10^{10} m^3 in 2012. Comparatively, fewer China's water footprint studies are related to water quality or water pollution. Wu and Ye (2020) elaborated water pollution shifting due to inter-province trade by gray water footprint of 30 provinces in China and found that 525 billion m^3 of net gray water footprint were shifted, mostly from Hebei, Shandong to Hunan, Henan. Wang et al. (2018) used EEIOA to account China's interregional flows of Chemical Oxygen Demand (COD) discharge and to explore its industrial and spatial characteristics (For example, virtual COD discharge in agriculture occupied 68.8% of the total flows, which were transferred from western regions to eastern regions over long distances). Zhao et al. (2016) analysed how Shanghai outsourced its pollution through virtual quality water flows, and the analyses indicated that 19 provinces experiencing water

quality stress endured 79% of net COD outsourcing and 75.5% of net NH_4^+ outsourcing from Shanghai.

3.4.3 Feasibility of Environmentally Extended Input-Output Analysis application for China's Water Footprint Studies

The reasons that lead to the lack of city-level studies (especially water quality studies) in the current literature are highly associated with the feasibility of EEIOA application for China's water footprint studies. And the major impediments were the absence of city-level environmentally extended input-output tables and the city-level water datasets include economic sectors that fully match these environmentally-extended input-output tables.

Regarding environmentally-extended input-output tables, Liu et al. (2012), Liu et al. (2014), and Mi et al. (2018) compiled multi-regional environmentally extended input-output tables across China's provinces in 2007, 2010 and 2012 respectively. But only until recently, Zheng et al. (2021b) released the 2015 multi-regional environmentally extended input-output table at the city level for the first time. To my best knowledge, no researcher has used this table for any studies yet.

For water datasets, water statistics in China's cities were patchy due to the city-level data unavailability, made worse by different statistic calibres in various official sources. For example, China statistic yearbooks quantified China's water pollution in the whole economic system while National Pollution Census (NPC) had sectoral water pollution in typical enterprises, and these statistics cannot be paired. Moreover, datasets for water quantity greatly outweighed those for water quality because water quality or water pollution was harder to quantify, especially non-point source pollution. Even though some researchers have constructed water datasets by hydrological models in a geographical grid unit for studies in river basins (Huang et al., 2021; Ma et al., 2020), water datasets of administrative units/cities in any particular river basin have not been compiled yet.

3.5 Research Gaps

This literature review identifies five research gaps that this thesis will address. First, the substantial growth of current knowledge regarding the influences of economy and development on water scarcity and water pollution could greatly benefit from water footprint research that links regional consumption with water impacts within and outside of a region (Yang et al., 2020). More studies are needed to investigate water footprint in the entire supply chain, involving inextricable relationships among water, production, consumption, and trade. Therefore, three case studies (Chapters 6, 8, and 9) in this thesis applied this method. Corresponding to Table 3-1, this thesis focuses on water footprint in the whole supply chain, which consists of multiple economic sectors, within a nation or in certain Given that such complex aspects have been covered, this thesis solely treat water footprint as a whole without examining the individual components separately. The exact methods to account water footprint are illustrated in Chapter 4. And water footprint assessment and corresponding strategies could be found in empirical work from Chapter 6 to Chapter 9.

Second, regarding the research scope of water footprint research: (1) There is an absence of city-level water footprint studies. Nevertheless, city-level studies are still of great value as the city is a basic administrative unit for a country to obtain, distribute and manage its water resources (Zheng et al., 2019). Hence, in this thesis, city-level water-energy nexus in the BTH region (Chapter 6) and water footprint in China's 313 cities (Chapter 8) were investigated for the first time. (2) Water footprint studies have focused more on water quantity and water scarcity than on water quality and water pollution. Therefore, this thesis extends the concept of water footprint and conducts wastewater footprint and eutrophication footprint by incorporating water quality indicators in water footprint (see Table 3-1). Two cases (Chapters 7 and 9) in this thesis involved water pollution indicators, COD discharge and NH_4^+ discharge.

Third, to bridge the main research gap of EEIOA, that is the absence of city-level EEIOA triggered by the lack of city-level environmentally extended input-output tables and city-level water datasets, we compiled the dataset for water withdrawal of all the cities across individual economic sectors in China for the very first time (Section 4.1.1) (Z. Zhang et al., 2020) and took the lead in applying these data in the city-level multi-regional environmentally extended input-output table (Section 4.2.2) compiled by Zheng et al. (2021b). Given that some water datasets, especially those for water quality or water pollution, cannot fully match EEIOA in the current stage, I also compiled a dataset for NH4+ discharge of all the cities in the PRB for the first time (Section 4.1.3).

Fourth, to my best knowledge, there is no research that traces anthropogenic sources of water pollutants discharged in specific administrative units/cities to a river basin. Thus, in this thesis, NH_4^+ discharge of all the cities in the PRB was accounted for the first time and these data were then analysed (Chapter 7).

Fifth, due to the limitation of some coupling research relevant to China's water scarcity and water pollution and its economy and development patterns, spatiotemporal characteristics and dynamics of economy and development and water scarcity and water pollution under specific contexts can be observed instead (Y. Liu et al., 2020a). However, as it is impossible to give an assessment of all the factors of economy and development activities and their interactions with water resources, this thesis only takes account of anthropogenic factors related to direct water withdrawal/consumption, which is more in line with the discipline of environmental economics. In this thesis, China's anthropogenic NH_4^+ discharge and relevant economy, development indicators in the PRB from 2011-2017 were observed together (Chapter 7), and China's water footprint patterns were analysed under China's several policy backgrounds regarding economy and development (Chapter 9).

Chapter 4 Methods

This thesis first compiles China's sectoral water datasets at national and city levels, and then applies a majority of these data in EEIOA. This chapter concretely introduces the compilation method and the data acquisition of these water datasets that provide quantitative inventories regarding water quantity (water withdrawal, water use) and water quality (COD, NH_4^+). All the water datasets were compiled across 42 economic sectors in primary/agricultural, secondary/industrial and tertiary/service industries (see Table A1) (except that NH_4^+ discharge dataset also includes household NH_4^+ discharge) in the entire country or in China's provinces/cities to perfectly match the requirement of EEIOA. This chapter also explicitly describes the structures and the basic elements in a single regional input-output table and a multi-regional input-output table, and how SREEIOA or MREEIOA were conducted in one year or in multiple years (by double deflation method).

4.1 Water Datasets

4.1.1 Water Withdrawal Dataset

In this thesis, Chapter 6 and Chapter 8 account city-level water withdrawal of the BTH region in 2012, and at the national scope in 2015 respectively. The compilation method of the city-level water withdrawal dataset was already elaborated in Z. Zhang et al. (2020), which can be shown in Figure 4-1. Table A2 shows data sources of all the indicators in this section. As one of the co-authors that participated in the data compilation, I then briefly introduce this method.

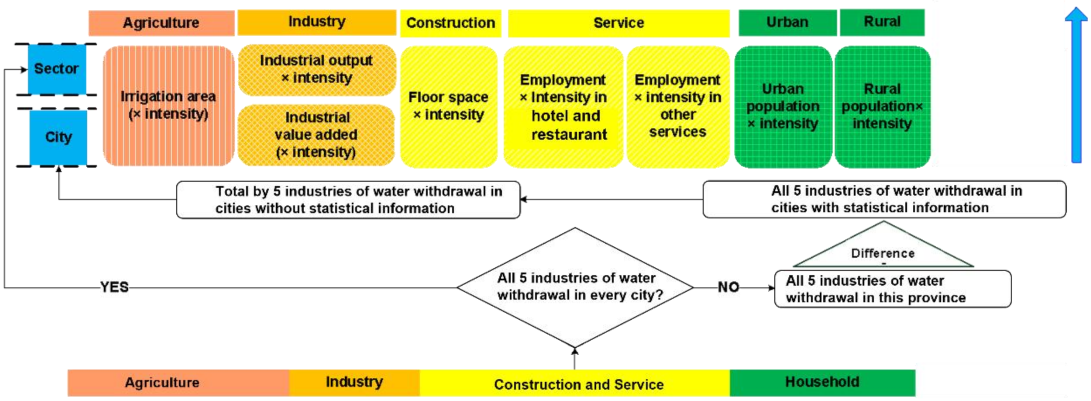

Figure 4- 1: Methodological framework of the city-level water withdrawal dataset. Source: Z. Zhang et al. (2020). Note: As a co-author in Z. Zhang et al. (2020), the other authors and I accounted city-level water withdrawal across 58 sectors. In this thesis, only 42 economic sectors (see Table A1) are included.

For primary industry, we first collected the total water withdrawal in a province and its cities with data availability, and summed the water withdrawal of the rest of cities in the province (denoted as $water_{psum}$). Second, we estimated water withdrawal in the rest of the cities under different circumstances: (1) If a city had irrigation/sown areas and irrigation water withdrawal per mu of farmland, water withdrawal in this city was directly obtained by multiplying these two factors. (2) For the other cities that solely had irrigation/sown areas, the sum of water withdrawal in these cities was downscaled with the ratios of their irrigation/sown areas. Then we calculated the ratio of water withdrawal in all the cities lacked statistics. Third, we collated the water withdrawal in the cities without data availability with the sum of water withdrawal ($water_{psum}$), and the ratio of water withdrawal in these cities to maintain data consistency. In the other provinces, water withdrawal of primary industry was compiled in the same way.

Regarding manufacturing industry (secondary industry except construction), we started by attaining the total water withdrawal in a province and its cities with available data, and calculated the sum of water withdrawal in the rest of the cities within the province (denoted as $water_{msum}$). We then estimated water withdrawal in the rest of the cities by multiplying total industrial value-added and water withdrawal per unit value-added in each city, and calculated the ratio of water withdrawal in these cities. To calibrate water withdrawal in these cities, we followed by downscaling the sum of water withdrawal ($water_{msum}$) with their ratio of water withdrawal. For individual sectors in each city, we used industrial water intensities (industrial water withdrawals divided by industrial outputs) of major enterprises, and industrial outputs to estimate industrial water withdrawals, and calculated its sectoral ratio. The water withdrawal across sectors in each city was then collated with the sum and the sectoral ratio of industrial water withdrawal in each city. The other provinces followed the same steps.

In terms of water withdrawal in construction and in tertiary industry, we collected the total water withdrawal in a province and its cities with data availability, and obtained the sum of water withdrawal in the rest of the cities (denoted as $water_{csum}$ and $water_{tsum}$ respectively). In these cities, water withdrawal in construction was estimated as floor space of housing multiplied by water withdrawal per unit floor space of housing, and water withdrawal in tertiary sectors was calculated as the multiplication of employment and water withdrawal per employee in each sector (water withdrawal per employee differed in hotel and restaurant from the other tertiary sectors). We then calculated the ratios of water withdrawal in construction and in tertiary sectors for the cities lacked data availability, followed by the calibration of water withdrawal in construction and in tertiary sectors in these cities with the sum of water withdrawal ($water_{csum}$ and $water_{tsum}$) and the ratios of water withdrawal in construction and in tertiary sectors. The other provinces applied the same compilation method.

4.1.2 NH_4^+ Discharge Dataset

In this thesis, Chapter 7 accounts NH_4^+ discharge of cities in the PRB in 2011 and 2017. To start with, cities in the PRB needed to be identified, and these cities were further categorised according to their administrative divisions, and their locations in the PRB's watershed zones (PRD; Dongjiang, Beijiang, Xijiang Rivers) (Table A3). Due to data missing, however, I accounted NH_4^+ discharge of all the cities in Yunnan, Guizhou, Guangxi, Guangdong, Jiangxi provinces, but only remained the data for the selected cities. Figure 4-2 depicts the methodological framework of the city-level NH_4^+ discharge dataset. Table A4 clarifies the data sources of all the indicators in this section.

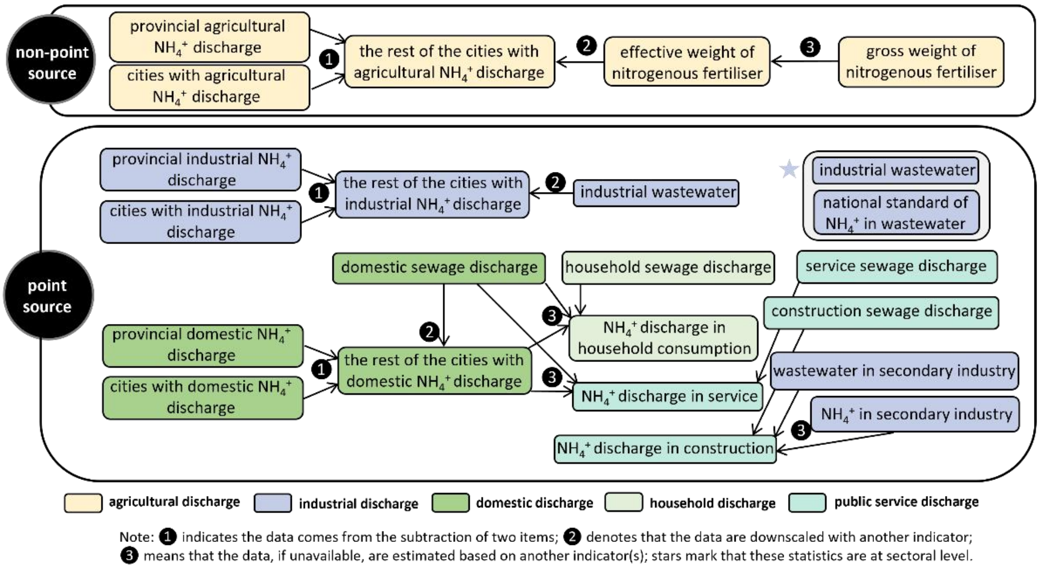

Figure 4- 2: Methodological framework of the city-level NH_4^+ discharge dataset

For primary industry, I first collected NH_4^+ discharge of a province in 2011, and predicted NH_4^+ discharge of the province in 2017 based on statistics in previous years. I then allocated the NH_4^+ discharge into each city within the province with the proportion of their effective weight of nitrogenous fertiliser. However, additional processes were required in these cases: 1) Providing a city only had a gross weight of nitrogenous fertiliser, its effective weight of nitrogenous fertiliser was estimated with the average conversion rate in the province. 2) If a city solely had a gross weight of chemical fertiliser, it was first converted to the effective weight of chemical fertiliser with the average conversion rate in the province, proceeded by the previous step. The other provinces repeated these procedures.

Regarding manufacturing industry (secondary industry except construction), I first acquired NH_4^+ discharge in a province and its cities with data availability, and downscaled the rest of NH_4^+ discharge with the ratio of industrial wastewater discharge in the other cities. For individual sectors in each city: 1) I utilised industrial wastewater intensities (industrial wastewater discharge divided by industrial outputs) of major enterprises, and industrial outputs to estimate industrial wastewater discharge. 2) I transformed industrial wastewater discharge into industrial NH_4^+ discharge according to national standards, and calculated the sectoral ratio. 3) I then distributed the total NH_4^+ discharge in each city into individual sectors with their sectoral ratios for data calibration. The other provinces went through the same process.

Domestic NH_4^+ discharge includes NH_4^+ discharge in household, construction and tertiary industry. I first accounted domestic NH_4^+ discharge. Domestic NH_4^+ discharge in a province and its cities with available data were collected, followed by the downscale of the rest of NH_4^+ discharge with the ratio of domestic sewage in the other cities within the province. When not all cities in the province held data for domestic sewage, the indicator to downscale was replaced by either domestic water use or domestic water supply. Then, I multiplied the ration between sewage in tertiary industry and domestic sewage, by domestic NH_4^+ discharge to estimate NH_4^+ of tertiary industry in each city. Similarly, I used the ratio between sewage in construction and in secondary industry, and secondary NH_4^+ discharge to obtain the NH_4^+ discharge of construction in each city. If these ratios were not accessible in a certain city, the average ratios between sewage in tertiary industry and domestic sewage, and between sewage in construction and secondary sewage of all the cities with known ratios were then taken as a replacement instead. Furthermore, household NH_4^+ discharge in each city was calculated by subtracting NH_4^+ discharge in tertiary industry and in construction from domestic NH_4^+ discharge. And the other provinces followed the same procedures.

4.1.3 Water Use and COD Discharge Datasets

In this thesis, Chapter 9 accounts the national level water use and COD discharge in 2010, 2012 and 2015 respectively. As the compilation is relatively straightforward, the methodological framework is not given in this section. Table A5 includes data sources of all the indicators mentioned in this section.

With regard to water use, I first collected China's water use in primary industry, manufacturing industry (secondary industry except construction), and domestic water use (water use in household, construction and tertiary industry). According to the calculation of Z. Zhang et al. (2020), the average percentages of water use in household, construction and tertiary industry accounted for 73.0%, 20.2% and 6.8% of domestic water withdrawal respectively. Thus, I multiplied domestic water use by 20.2% and 6.8% to obtain China's water use in construction and in tertiary industry respectively. For individual economic sectors: (1) Sectoral manufacturing water use (included water reuse) was directly accessed, and their sectoral ratio was calculated. In order to guarantee data consistency, sectoral manufacturing water use (excluded water reuse) was calibrated with the previously collected total manufacturing water use (excluded water reuse) with the sectoral ratio of manufacturing water use (included water use). (2) Tertiary industry's Water use was distributed into each tertiary sector on the basis of corresponding employee numbers.

As for COD discharge, I first gathered the data of China's COD discharge in primary industry, manufacturing industry (secondary industry except construction), and domestic COD discharge (COD discharge in household, construction and tertiary industry). Similarly, COD discharge in construction and tertiary industry needed to be separated from domestic COD discharge. Based on my calculation, the percentage of employee numbers in construction and tertiary industry accounted for 58% of the total population in China. Considering that employees not only discharged COD in construction and tertiary industry (during work), but also discharged household COD (off work), I then multiplied the original percentage by 8/24 (8 working hours per day), and the newly-obtained percentage was approximately 19%. Therefore, COD discharged in construction and tertiary industry was calculated as 19% of the domestic COD discharge. For individual economic sectors: (1) Sectoral manufacturing COD discharge was directly accessed. (2) COD discharge in construction and tertiary industry was further downscaled into construction and individual tertiary sectors with the number of employees.

4.2 Environmentally Extended Input-Output Analysis

EEIOA is based on input-output tables. This section presents the basic structures of single regional and multi-regional input-output tables, and how EEIOA is conducted on the basis of these tables. In this section, matrixes are indicated by bold, upright capital letters; vectors by bold, upright lower-case letters; scalars by italicised letters; and a diagonal matrix by a circumflex.

4.2.1 Single Regional Environmentally Extended Input-Output Analysis

SREEIOA can solely account virtual water of a single area. China's single regional input-output table includes n economic sectors (n=42) as attached in Table A1, and the basic layout of a single regional input-output table is illustrated in Figure 4-3 (in monetary terms). In this input-output table, **Z** represents intermediate demand matrix that depicts transactions between pairs of sectors from sector i to sector j; **f** stands for domestic final demand, which incorporates rural consumption, urban consumption, government expenditure, capital formation (fixed capital and inventory increase); **e** is known as export and **m** is import; **x** is total output. In addition, superscript d means that the indicators are for domestic production, and superscript m represents that the indicators are for import.

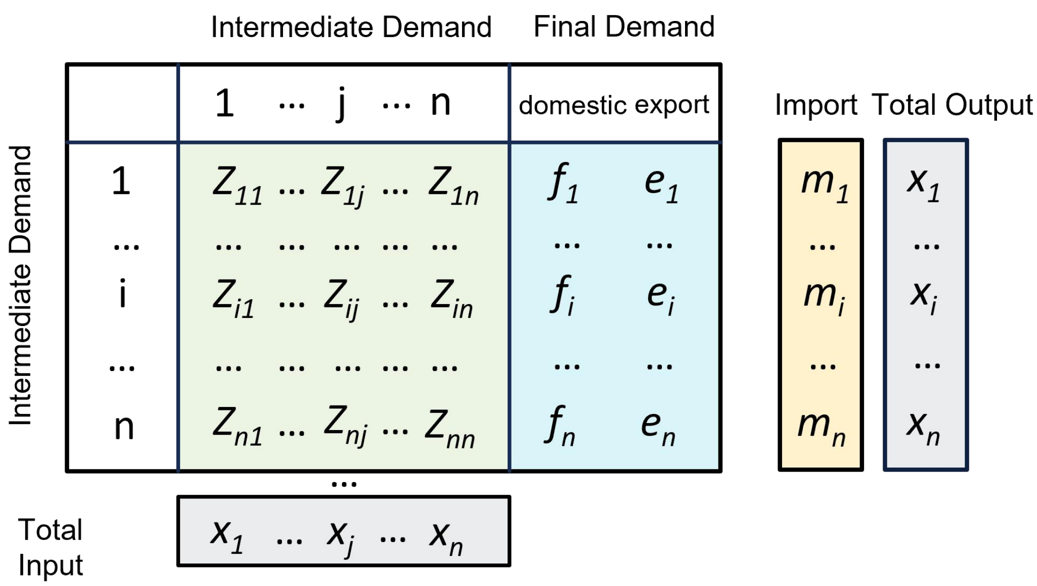

Figure 4-3: Basic layout of China's single-regional input-output table. Note: the basic layout of single-regional input-output table is based on Miller and Blair (2012).

For SREEIOA, the effect of intermediary/entrepot trade needs to be eliminated by applying the methods validated by Dietzenbacher et al. (2013). Whether a country or a city contains intermediary trade should first be judge by indicator **it**, where:

$$it_i = m_i - \sum_{j=1}^{n} Z_{ij} - f_i \ (i = 1, 2, ..., n) \quad (4\text{-}1)$$

If $IT_i < 0$, the intermediate trade does not exist. On the contrary, if $it_i > 0$, then intermediary trade should be removed. In the single regional input-output table, the column for export consists of export to domestic market (**ed**), and export to international market (**ei**), and the column for import includes import from domestic market (**md**), and import from international market (**mi**). When $it_i < 0$, the adjusted ed_i (aed_i), ei_i (aei_i), md_i (amd_i), mi_i (ami_i) remain the same values as the original ed_i, ei_i, md_i, mi_i. When $it_i > 0$, aed_i, aei_i, amd_i, ami_i are calculated as:

$$aed_i = ed_i - it_i \times \frac{ed_i}{e_i} \ (i = 1, 2, ..., n) \quad (4\text{-}2)$$

$$aei_i = ei_i - it_i \times \frac{ei_i}{e_i} \ (i = 1, 2, ..., n) \quad (4\text{-}3)$$

$$amd_i = md_i - it_i \times \frac{md_i}{m_i} \ (i = 1, 2, ..., n) \quad (4\text{-}4)$$

$$ami_i = mi_i - it_i \times \frac{mi_i}{m_i} \ (i = 1, 2, ..., n) \quad (4\text{-}5)$$

Given that China has competitive input-output tables (**Z** and **f** do not distinguish the effects of domestic consumption and import), it is necessary to isolate $\mathbf{Z^d}$ from **Z**, $\mathbf{f^d}$, from **f**. The proportions of $\mathbf{Z^d}$ in **Z**, $\mathbf{f^d}$ in **f** can be estimated as $\boldsymbol{\alpha}$:

$$\alpha_i = 1 - \frac{amd_i + ami_i}{(x_i + amd_i + ami_i - aed_i - aei_i)}$$
$$= 1 - \frac{amd_i + ami_i}{\left(\sum_{j=1}^{n} Z_{ij} + f_i + e_i - m_i + amd_i + ami_i - aed_i - aei_i\right)}$$
$$\approx 1 - \frac{mi_i}{\left(\sum_{j=1}^{n} Z_{ij} + f_i\right)} \ (i = 1, 2, ..., n) \quad (4\text{-}6)$$

$\mathbf{Z^d}$, $\mathbf{f^d}$ can then be obtained:

$$\mathbf{Z^d} = \mathbf{Z} \times \boldsymbol{\alpha} \quad (4\text{-}7)$$

$$\mathbf{f^d} = \mathbf{f} \times \boldsymbol{\alpha} \quad (4\text{-}8)$$

After the new intermediate demand matrix $\mathbf{Z^d}$ and the new vector for final demand $\mathbf{f^d}$ are generated, the technical coefficient matrix **A**, and Leontief inverse matrix **L** should then be introduced. Technical coefficient a_{ij} denotes the ratio of the input of sector i to the output of sector j in monetary units:

$$a^d{}_{ij} = \frac{Z^d{}_{ij}}{x_j} \ (i, j = 1, 2, ..., n) \quad (4\text{-}9)$$

To explain Leontief inverse matrix **L**, the basic equations 4- 10 and 4- 11 in the original input-output table are first presented. Based on the transformation of equation 4- 9, equation 4- 12 is rewritten, where **I** is the n x n identify matrix with ones on the main diagonal and zeros elsewhere. This equation clarifies the definition of **L**, and intermediate demand and total output driven by each category of final demand in individual economic sectors can be made clear.

$$\mathbf{fem} = \mathbf{f} + \mathbf{e} - \mathbf{m} \quad (4\text{-}10)$$

$$\mathbf{x} = \mathbf{Z} + \mathbf{fem} \quad (4\text{-}11)$$

$$\begin{aligned} \mathbf{x} &= \mathbf{A} \times \mathbf{x} + \mathbf{fem} \\ &= (\mathbf{I} - \mathbf{A})^{-1} \times \mathbf{fem} \\ &= \mathbf{L} \times \mathbf{fem} \end{aligned} \quad (4\text{-}12)$$

Based on equation 4- 6and equation 4- 12, $\mathbf{L^d}$ can be calculated as:

$$\mathbf{L^d} = \left(\mathbf{I} - \mathbf{A^d}\right)^{-1} \quad (4\text{-}13)$$

In EEIOA, a factor that considers environmental impact is essential. For instance, in order to account embodied water withdrawal in a country or a city, direct water intensity $\boldsymbol{\varepsilon}^{\mathbf{d}}$ need to be calculated, where **dw** is the direct water withdrawal accounted in Section 4.1.1.

$$\varepsilon^{\mathrm{d}}{}_i = \frac{dw_i}{x_i} \ (i = 1, 2, \dots, n) \quad (4\text{-}14)$$

And the embodied water withdrawal to meet domestic consumption (**WDC**) and to satisfy export (**WE**) can be described as:

$$\mathbf{WDC} = \widehat{\boldsymbol{\varepsilon}^{\mathbf{d}}} \times \mathbf{L^d} \times \widehat{\mathbf{f^d}} \quad (4\text{-}15)$$

$$\mathbf{WE} = \widehat{\boldsymbol{\varepsilon}^{\mathbf{d}}} \times \mathbf{L^d} \times \widehat{\mathbf{e}} \quad (4\text{-}16)$$

In order to further account water withdrawal embodied in import (**WI**) in a city (not applicable to a country), $\mathbf{L^m}$ and $\boldsymbol{\varepsilon}^{\mathbf{m}}$ should be acquired. $\mathbf{L^m}$ and $\boldsymbol{\varepsilon}^{\mathbf{m}}$ represent the average technological coefficient and average direct water withdrawal intensity of this city's multiple importers. Unfortunately, SREEIOA is unable to specify this city's virtual water importers. Hence, this city's $\mathbf{L^m}$ and $\boldsymbol{\varepsilon}^{\mathbf{m}}$ are estimated to be equivalent to the whole country's $\mathbf{L^d}$ and $\boldsymbol{\varepsilon}^{\mathbf{d}}$. And the city's **WI** is written as:

$$\mathbf{WI} = \widehat{\boldsymbol{\varepsilon}^{\mathbf{m}}} \times \mathbf{L^m} \times \widehat{\mathbf{m}} \quad (4\text{-}17)$$

Figure 4- 4 demonstrates the basic structure of matrixes of **WDC**, **WE** and **WI** (taking **WDC** in city K as an example).

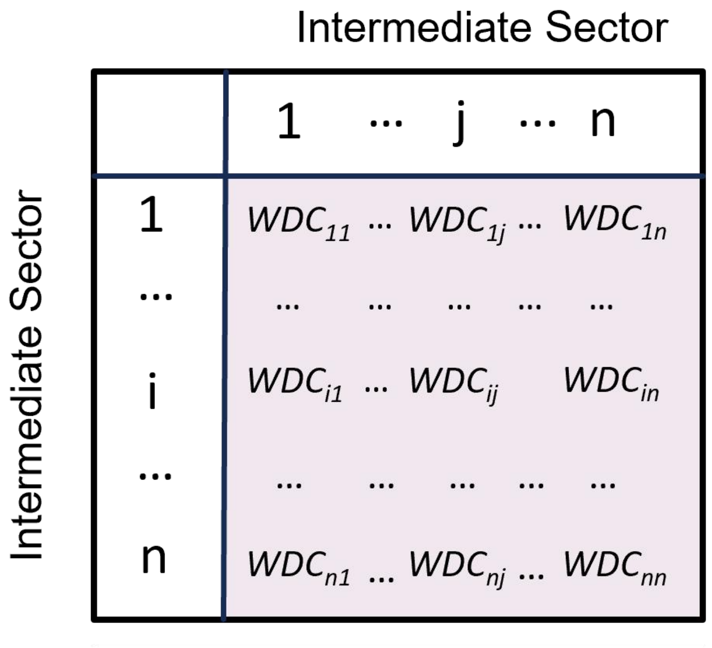

Figure 4- 4: Basic structure of the WDC matrix. Note: the basic structure of the WDC matrix is based on is based on Miller and Blair (2012).

If all the values in column j are added up, the sum represents the inflow of embodied water withdrawal to sector j from all the sectors (including itself) in order to meet city K's domestic consumption/export/import. If all the values in row i are added up, the sum means the outflow of embodied water withdrawal in sector i to all the sectors (including itself) in order to meet city K's domestic consumption/export/import. If all the values in the matrix are added up, the sum indicates the total embodied water withdrawal that city K requires in order to meet its domestic consumption/export/import.

In this thesis, SREEIOA was applied at the national and city levels to support the results in Chapter 9 and Chapter 6 respectively. In Chapter 4, the embodied water withdrawal was the sum of WDC and WI. In Chapter 6, the embodied water use and COD discharge was the sum of WDC and WE. The 2010, 2012 and 2015 national single regional input-output tables were obtained from Chinese Input-Output Associate (CIOA) (CIOA, 2010-2015), while the 2012 single regional input-output tables of thirteen cities in the BTH region were compiled by local governments.

4.2.2 Multiple Regional Environmentally Extended Input-Output Analysis

MREEIOA is capable of tracing inflows and outflows of virtual water among multiple areas, and clearly identifying virtual water importers and virtual water exporters for any of the areas. Comparatively, MREEIOA is more straightforward than SREEIOA because there is no need to consider intermediary/entrepot trade and the isolation of domestic consumption and import. Yet data volume in MREEIOA is much larger than that in SREEIOA. China's multi-regional input-output table includes n economic sectors (n=42) for each area as attached in Table A1, and the basic layout of a multi-regional input-output table is shown in Figure 4- 5 (in monetary terms).

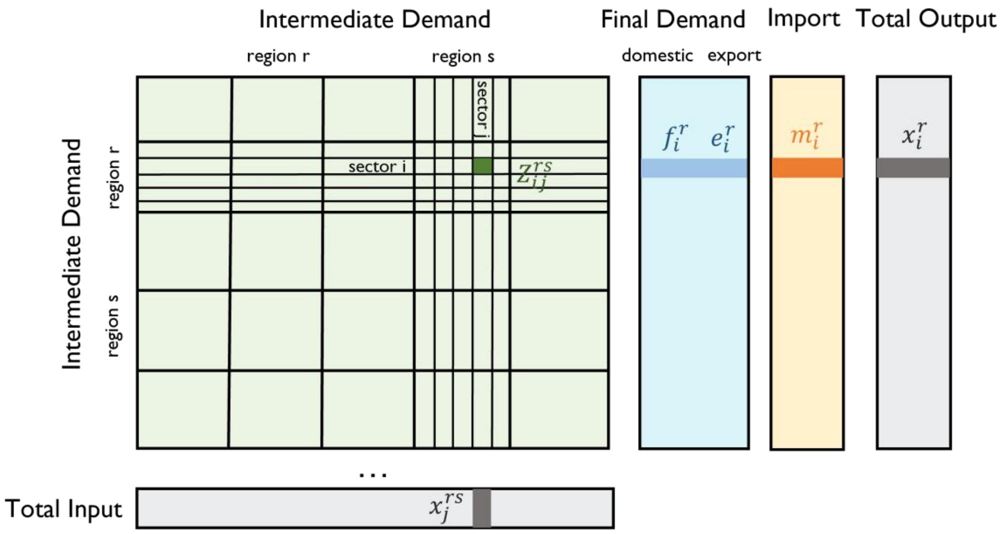

Figure 4- 5: Basic layout of China's multi-regional input-output table. Note: the basic layout of multiple-regional input-output table is based on Miller and Blair (2012).

Similar to a single regional input-output table, **Z**, **f**, **e**, **m**, **x** represent intermediate demand matrix; domestic final demand that incorporates rural consumption, urban consumption, government expenditure, and capital formation (fixed capital and inventory change); export; import; total output respectively. In a multiple-regional input-output table, however, **Z** includes multiple sub-matrixes, and **f**, **e**, **m** include multiple vectors for each of the areas. For instance, in order to account embodied water withdrawal in China's city-level multi-regional input-output table, u administrative units (u=313) are included as indicated in Table A6, and hence **Z** has u sub-matrixes, and **f**, **e**, **m** have u vectors. Z_{ij}^{rs} indicates the intermediate demand of sector j in region s met by sector i in region r. f_i^{rs}, e_i^{rs} and m_i^{rs} denote domestic demand, export, and import of sector i in region r driven by region s. Then **f, e, m**, **x** and **Z** can be expressed as:

$$f_i^r = f_i^{r1} + \dots + f_i^{ru} \; (i = 1, 2, \dots, n; r = 1, 2, \dots, u) \tag{4- 18}$$

$$e_i^r = e_i^{r1} + \dots + e_i^{ru} \; (i = 1, 2, \dots, n; r = 1, 2, \dots, u) \tag{4- 19}$$

$$m_i^r = m_i^{r1} + \dots + m_i^{rm} \; (i = 1, 2, \dots, n; r = 1, 2, \dots, u) \tag{4- 20}$$

$$\begin{aligned} x_i^r &= \left(Z_{i1}^{r1} + \dots Z_{in}^{r1} \right) + \dots + \left(Z_{i1}^{ru} + \dots Z_{in}^{ru} \right) + f_i^{r1} + \dots + f_i^{ru} \\ &\quad + e_i^{r1} + \dots + e_i^{ru} - \left(m_i^{r1} + \dots + m_i^{ru} \right) \\ &= \sum_{s=1}^{u} \sum_{j=1}^{n} Z_{ij}^{rs} + \sum_{s=1}^{u} f_i^{rs} + \sum_{s=1}^{u} e_i^{rs} - \sum_{s=1}^{u} m_i^{rs} \\ &\quad (i = 1, 2, \dots, n; r = 1, 2, \dots, u) \end{aligned} \tag{4- 21}$$

In the multi-regional input-output table, **A** represents technical matrix, and a_{ij}^{rs} indicates the input of sector i in region r in order to produce per unit output of sector j in region s:

$$a_{ij}^{rs} = \frac{Z_{ij}^{rs}}{X_j^{rs}} \; (i, j = 1, 2, \dots, n; r, s = 1, 2, \dots, u) \qquad (4\text{-}22)$$

Following the basic equations in an input-output table, Leontief matrix inverse matrix **L** is written as $(\mathbf{I} - \mathbf{A})^{-1}$. **I** is the n x u identify matrix with ones on the main diagonal and zeros elsewhere. And environmental factor, in this case, direct water intensity **ε** is calculated, where **dw** is the direct water withdrawal accounted in Section 4.1.1.

$$\varepsilon_i^r = \frac{dw_i^r}{X_i^r} \; (i = 1, 2, \dots, n; r = 1, 2, \dots, u) \qquad (4\text{-}23)$$

Accordingly, the embodied water withdrawal to meet domestic consumption (**WDC**) and to satisfy export (**WE**) can be calculated as follow. The embodied water withdrawal in import (WI) in MREEIOA needs not to be estimated, as China's WI can be calculated in global multi-regional input-output tables, such as Global Trade Analysis Project (GTAP), World Input-Output Database (WIOD), EORA (The Eora Global Supply Chain Database), and EXIOBASE.

$$\mathbf{WDC} = \hat{\boldsymbol{\varepsilon}} \times \mathbf{L} \times \hat{\mathbf{f}} \qquad (4\text{-}24)$$

$$\mathbf{WE} = \hat{\boldsymbol{\varepsilon}} \times \mathbf{L} \times \hat{\mathbf{e}} \qquad (4\text{-}25)$$

Figure 4- 6 depicts the structure of matrixes of **WDC** and **WE**.

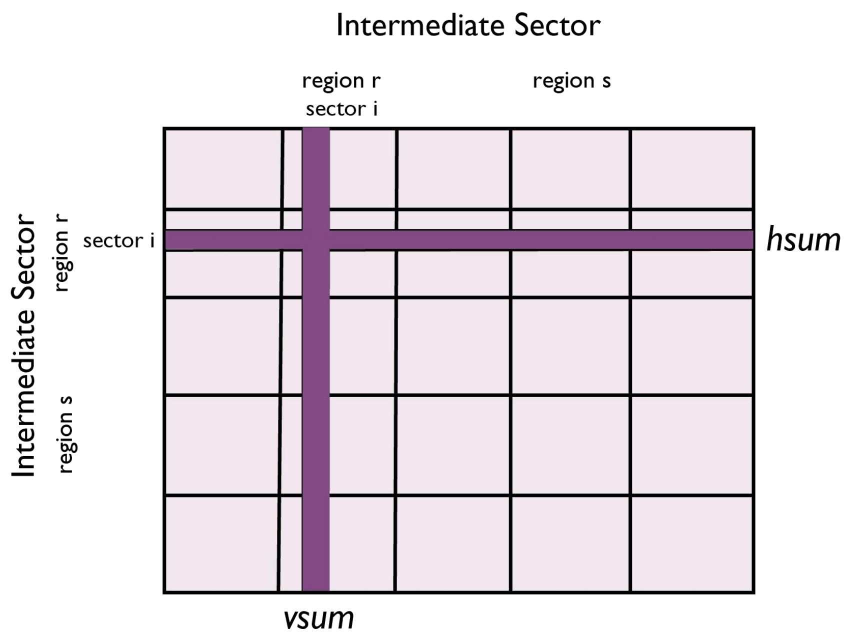

Figure 4- 6: Basic structure of the WDC and WE matrix. Note: the basic structure of the WDC matrix is based on Miller and Blair (2012).

If all the values of column i in region r are added up as *vsum*, the sum represents the inflow of embodied water withdrawal to sector i in region r from all the sectors in all the cities (including sector i in region r) in order to meet the whole country's domestic consumption/export. If all the values of row i in region r are added up as *hsum*, the sum means the outflow of embodied water withdrawal in sector i, region r to all the sectors (including sector i in region r) in order to meet the whole country's domestic consumption/export. Then the difference between *vsum* and *hsum* can tell whether region r's sector i is a net water import (*vsum* > *hsum*), or a net water exporter (*vsum* < *hsum*).

In this thesis, MREEIOA was applied at the city level to support the results in Chapter 8, where the embodied water withdrawal was the sum of WDC and WE. The 2015 city-level multi-regional input-output table was compiled by Zheng et al. (2021b), including 4 provinces and 309 cities (Table A6).

4.2.3 Double Deflation Method for Environmentally Extended Input-Output Analysis in Multiple Years

Assuming water footprints in multiple years are accounted, all the input-output tables should be converted to constant prices in the base year to remove the effect of inflation, and the double deflation method is often applied. Figure 4- 7 uses a single-regional input-output table to explain how to transform matrixes and vectors in current prices into constant prices (described with subscript def) of n economic sectors (Table A1) in the input-output table.

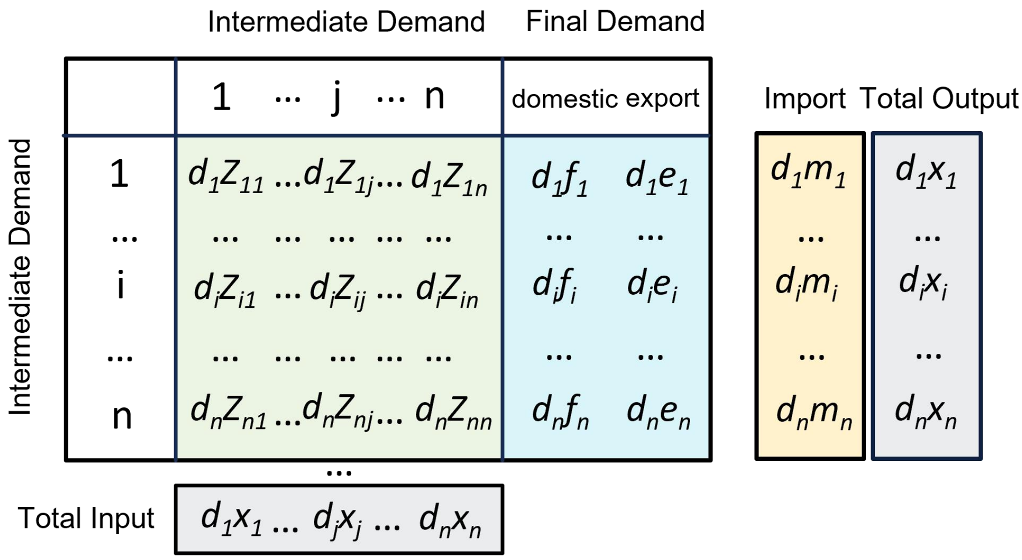

Figure 4- 7: Conversion of matrixes and vectors in current prices into constant prices in China's single-regional input-output table. Note: the method to converse the matrixes and vectors in current prices into constant prices is based on Miller and Blair (2012).

Given the **p** denotes the ratios of the current prices and the base year prices in n sectors, **d** indicates the reciprocal price ratios, or the deflators in n sector, as:

$$d_i = \frac{1}{p_i} \; (i = 1, 2, \ldots, n) \tag{4- 26}$$

In the input-output table, yearly producer price indexes (PPIs) in n sectors are taken as the indicator to measure deflators as all the elements are closely associated with production. Given that China solely has PPIs for primary and secondary sectors, PPIs in tertiary sectors are estimated: (1) PPIs were not applicable in scientific research (S36), water conservancy (S37) and public management (S42) as government services do not comply with market disciplines so **z**, **f**, and **x** in these sectors remain unchanged. (2) In the other tertiary sectors, PPIs were replaced by CPIs.

In this thesis, double deflation method was applied in Chapter 9, when multiple years' SREEIOA were conducted in China on a national scope. The application of double deflation method occurred before the removal of effects triggered by intermediary/entrepot trade, as mentioned in equation 4- 6. PPIs and CPIs were obtained in China statistic yearbooks (NBS, 2010-2015).

4.3 Limitations and Future Work

The current methods have limitations:
Frist, due to the lack of data transparency, the current compilation method of the water datasets (Section 3.1) (especially city-level water datasets) were often based on literature, reasonable but strong assumptions, made worse by the difficulty to validate the data accuracy by sensitivity/uncertainty analysis. As a novel and ground-breaking work, however, the method has a huge room for improvement in the future when more water data become available.
Second, restricted by data availability, primary industry, unlike secondary and tertiary industry, was not further split into sub-sectors (agriculture, forestry, husbandry, and fishing), or even into different types of crops and livestock, in the input-output tables and the water datasets.
Third, unlike national level single regional input-output tables and city-level single regional input-output tables in the BTH region (Section 4.2.1), the city-level multi-regional input-output table (Section 4.2.2) was compiled by a research group based on China's provincial-level single regional input-output tables, without the scrutinization of the governments yet (Zheng et al., 2021). But since one of the most critical innovations of this thesis is to account virtual water flows among China's cities, this input-output table is indispensable in the current stage.
Fourth, in the double deflation method (Section 4.2.3), each sector's intermediate demand, final demand and total output are all deflated by an identical price index that represents the entire sector, which neglects the diversity of product portfolio that these sectors supply to different consumers (Guan et al., 2014).
Fifth, uncertainties in water footprint accounting might be significant but uncertainty studies are currently not available for water footprint research Hoekstra et al. (2011). There is no an effective way to measure error ranges either if an uncertainty analysis is not carried out.

For future work, some ideas have been formed and could be further developed:
(1) In order to further probe into specific economic or societal factors that contribute to the changes of water footprint over time, Structure Decomposition Analysis (SDA) could be considered. Structure Decomposition Analysis (SDA) is a method that can

identify certain driving forces (normally include population, water intensity, production efficiency, consumption patterns, and per capita consumption volume) of changes in embodied water in EEIOA. To conduct this method, however, the data availability of water datasets and input-output tables should be guaranteed first as water datasets and input-output tables for at least three years with the same year interval are the prerequisites. Without data support, the SDA cannot be applied either.

(2) It is possible to project future water footprint under alternative socio-economic pathway scenarios based on current results obtained from EEIOA (X. Xu et al., 2020), instead of solely concentrating on historical accounting and tread analysis. But similarly, this forecasting is usually analysed with statistical or simulation models and it requires long-term and accurate historical data so as to generate reliable results.

(3) Nutrient footprint, especially NH_4^+ discharge footprint, could also be accounted in China. Some researchers have applied EEIOA to account nutrient footprints at the global level (Hamilton et al., 2018; Oita et al., 2016). Yet there are limited China's Nutrient footprint studies at the national, provincial levels, or in China's 313 cities due to the absence of comprehensive nutrient datasets. To our best knowledge, however, Qian et al. (2022) has released a regional input-output table in the PRB, which means that it is highly likely that inter-city NH_4^+ discharge footprint in the PRB could be accounted first in the near future.

Chapter 5 Policy Landscape

This chapter serves two purposes: It gives a landscape of China's water management policy, both the overall management framework and policy in key sectors with large volumes of water use. It not only identifies responsible authorities under different contexts but also describes existing efforts made in the water management while maintaining its economic growth and development. More importantly, this chapter specifies some water policy and guiding principles to better contextualise the findings in the following empirical chapters (Chapters 6-9) and to better ground corresponding policy recommendations (Section 11.3), which lay great foundations for the discussions of potential ways for institutional and policy interventions to address the evolving relationship between China's economy, development and water management.

5.1 China's Water Management Framework

5.1.1 Water Planning and Water Management in River Basins/Administrative Units

This section starts with China's water management framework, especially water planning and water management in river basins/administrative units. It is because that a country's water management is closely associated with its socioeconomic development, and river basins/administrative units are basic units for all types of anthropogenic activities. In Section 5.1.1, most of the information was sourced from Laws of the People's Republic of China on water (CSC, 2018).

In China, all water resources (surface water and underground water) are owned by the State Council, except water resources in ponds or reservoirs governed by rural organisations with collective economy. The State Council's Department for Development Planning and Department of Water Administration are responsible for the macroscopic allocation of national water resources.

China's water planning could be divided into integrated water planning and specialised water planning. Integrated water planning aims to develop, utilise, conserve, protect and manage water resources, while specialised water planning targets at water resources in specific areas, such as irrigation water or water resources for hydro-power. If conflict exists, specialised water planning should be subject to integrated water planning.

In China, the State Council's water management system is also a combination of watershed water management and administrative water management. The State Council's Department of Water Administration establishes river basin authorities, and governments at or above county level are responsible for the management and supervision of water resources in respective administrative units in the reiver basins. When a river basin is solely located in one administrative unit, water policy is drafted by the State Council's Department of Water Administration and corresponding administrative units, and finally approved by the State Council. If a river basin covers multiple administrative units, water policy will be drafted by all the administrative units in the river basin, and finally approved by the State Council. Meanwhile, administrative units have their own water policies. The medium- and long-term water supply and demand planning in provinces/autonomous regions/cities are made by the State Council's Department of Water Administration and approved by the State Council, while medium- and long-term water supply and demand planning for administrative units at or above the county level are made and approved by their local governments. However, administrative water management policy should be subject to watershed management policy for administrative units located in river basins.

5.1.2 Water Distribution, Water License, Water Pricing and Water Subsidy

This section covers four important components in China's water management framework: water distribution, water license, water pricing and water subsidy. Most of the information about water distribution is obtained from CSC (2018), and most of the information about water license, water pricing and water subsidy was sourced from the State Council (2016).

Speaking of water distribution, China not only controls the total volume of water distribution but also implements water quota management. China makes annual plans about water distribution in important rivers/lakes. An industrial administration in a province/autonomous region/city could decide on its industrial water quota and report it to the water administration in the province/autonomous region/city. Government of the province/autonomous region/city then announces the industrial water quota and reports it to the State Council's Department of Water Administration and the State Council's Department of Quality Supervision.

Once the water resources are distributed, it involves the license system of water withdrawal, and water pricing for water resources. The license system of water withdrawal indicates that industries or companies that would like to directly withdraw surface or groundwater need to obtain a water license first and then pay water fees (Groundwater costs are higher than surface water costs for the balance of groundwater exploitation and replenishment and for ecological environment conservation).

Water pricing refers to the methods by which the costs of providing water services are allocated to the users of those services, and it is normally the setting of tariffs or charges in order to achieve more efficient water use (European Environmental Agency, 2013). China executes both 'two-part water pricing' and 'seasonal water pricing'. 'Two-part water pricing' is named as its water prices include a basic price with fixed amount of water quota and metered water prices that charge for water use exceeds the fixed water quota. 'Two-part water pricing' is designated for industries with large amounts of water use with significant annual changes, especially agriculture. It is because that these industries are greatly influenced by hydrological and meteorological factors and their actual production might vary in different hydrological years. Hence, the implement of 'two-part water pricing' could not only alleviate excessive water supply but also improve water users' water-saving awareness. 'Seasonal water pricing' has two different water prices during rainy and dry seasons, which is mainly targeted for industries with huge seasonal differences in water use.

Sophisticated water pricing mechanism is a good foundation for the establishment of precise water subsidy schemes. As one of the environmental subsidies, water subsidy is payment by the government that is intended to support activities which protect the environment or reduce the use of water resources (UN, 2012). As incentives to offset costs of mandatory water standards or to change water use behaviours, water subsidy comes in many forms such as grants, loans, and tax relief. In China, the government allocates funds to water projects. For example, the Ministry of Finance and the Ministry of Housing and Urban-Rural Development (2019) released 'Subsidies for Urban Pipeline Networks and Sewage Treatment' in order to tackle water issues such as the construction of sponge city or the restoration of black and odorous water. China also aims to establish an easy-to-operate and widely accepted water-saving incentive mechanism by giving rewards to organisations and individuals who take water-saving measures or invoke enthusiasm for water-savers.

5.2 Guiding Principles

5.2.1 Water Rights Trade

Water rights trade is the process of buying and selling water access entitlements, empowering water right holders to utilise market mechanisms and trade a part of water resources to other water users. Here, water rights refer to the rights to use water resources as the ownership of China's water resources belongs to the country (MWR. 2005). The establishment of tradeable water rights is considered as key management instrument to incentivise water-use efficiency, equality and sustainability, especially in development countries such as China. It formalises and secures the existing water rights held by water users and induces all water users to consider the full opportunity cost of water (Rosegrant and Binswanger, 1994; Zheng et al., 2021a). Under this circumstance, water rights trade also reshapes the economy and promotes social development. This is because that water rights trade essentially encourages water users to adjust their water/economic structure, to reform water techniques or to change their water behaviours.

In July 2014, China launched pilot projects of water markets in 7 provinces, including Inner Mongolia, Henan, Gansu, Guangdong, Ningxia, Jiangxi, Hubei. In June 2016, China Water Exchange, the national-level water rights trade cloud platform, was funded by MWR with the consent of the State of the Council. In the meanwhile, several regulations were released to supervise the water rights trade. In April 2016, MWR announced the 'Interim Measures for the Administration of Water Rights Trade' (MWR, 2016). In August 2022, MWR, National Development and Reform Commission, and Ministry of Finance jointly issued the 'Guiding Opinions on Promoting Water Rights Reform' (MWR, 2022a). The following information are mostly obtained from these sources.

In order to better understand the mechanism of China's water rights trade, the following aspects need to be considered: main bodies of water rights trade, classification in water rights trade, and challenges that it faces. The main bodies of water rights trade include central government (who takes a role as a server and a supervisor) and water users/traders. Central government is responsible for making initial distribution of water rights, establishing water rights marketplace/information system and encouraging public participation, developing laws/regulations and supervising water trade, constructing infrastructures for water trade, and dealing with contradiction and dispute in water rights trade. Water users are those who trade water rights but they also have the obligation to report other water users' abnormal behaviours in water rights trade. Of water traders, owners of water rights could sell and appropriate water rights to other water users.

China's water rights trade market is triple-tiered:

- The first tier: Water rights trade between central government and regional governments.
- The second tier: Water rights trade among regional governments. After central government sets up water rights quotas in each individual region, regional governments could trade water rights among regions by themselves with consideration of their own water conditions (such as water scarcity, water efficiency and water-saving costs). In this tier, a market mechanism is officially introduced even though the market subjects are still governments.
- The third tier: Water rights trade between water users. When water rights are ultimately allocated or sold to water users by regional governments, water users are able to trade water rights based on their own water demand.

In China, the main water type in water rights trade is surface water. But it might come in many forms with differences in types of water rights trade (such as regional water rights trade, water withdrawal rights trade, irrigation water rights trade), in time limits (such as permanent/continuous water rights trade, long-term water rights trade, and short-term/temporary trade), or in the extent of water rights trade (whole water rights trade or partial water rights trade).

Nevertheless, China's water rights trade still confronts with several challenges (Gao, 2022):

- There is insufficient top-level design for defining suitable water rights quota. In the current stage, several water users still rely on governments and obtain their water resources by applying for water quotas. However, the distributed water quotas might not be compatible with either their socioeconomic development or their carrying capacity of water resources, water ecology and water environment. And geographically, water users in water-rich Southern area are more active than those in water-scarce Northern area. Therefore, analysing China's water footprint accounting could greatly help policy makers define water quotas in different in administrative units/industries/economic sectors, which will be further discussed in Chapter 11.
- There is no a standardised water rights trade platform and the existing
- platforms are lack of supervision. Except China Water Exchange, there are several regional-level water rights trade platforms but they adhere to different water rights trade rules. Hence, China sets the goals of establishing a unified national water rights trade market by 2025, and claims its ambition to build a

comprehensive system for water rights trade by 2035.
- Third, there is a lack of capital investment and infrastructure.

5.2.2 Other Guiding Principles
There are several other guiding principles:
- Development economics. Development is a branch of economics that aims to improve fiscal, economic and social conditions in developing countries, such as China. Many economists support economic development instead of economic growth, where economic development refers to sustainable and high-quality economic growth that is compatible with social development. On the basis of this principle, China's government came up with its own economic concepts such as the 'New Normal' (Mi et al., 2017), a very important concept that appears in Chapter 9.
- Circular economy. Circular economy is an economy and development mode characterised by resource recycling and utilisation, and it emphasises environmental harmony and associates with a healthy water cycle to a great extent (Sauvé et al., 2021). China introduced this concept and abided by the principles of 'reduce, reuse, recycle' (National Development and Reform Commission, 2021). During the 13th five-year plan (from 2016 to 2020), China's circular economy has advanced greatly, and 9 billion-tonne wastewater discharge and was saved solely in 2014. In July 2021, China further issued the 'Development Plans about Circular Economy in the 14th Fiver-Year Plan', and set the target to reduce water use per unit of GDP by 16% from 2020-2025.
- Interregional Cooperation. In 'The 14th Five-Year Plan for National Economy and Social Development and the Outline of Long-Term Objectives of 2035 for People's Republic of China', China takes interregional collaboration as a crucial measure to co-manage water management (GOV, 2021b).

5.3 Water Management in Key Sectors

This section concentrates on water resources management in China's key sectors with large water volumes, which are irrigation water in agriculture, hydroelectricity/hydroelectric power, and urban water supply.

5.3.1 Irrigation Water in Agriculture
Most of the information of this section was sourced from MWR (2022b). China has been putting great efforts in managing irrigation water in agriculture by taking several measures in irrigation areas, especially medium- and large-sized irrigation areas. One of the most important measures is constructing water infrastructure. They include the advancement of irrigation water supply metering facilities and the promotion of irrigation and drainage engineering projects, such as anti-seepage channels, pipeline reconstruction to reduce leakage and losses during water transmission and water distribution. Introducing new technologies/equipment greatly strengthens the adaptability of water resources and enhances water resource carrying capacity. However, the modernisation of water infrastructure is inseparable from water subsidies, which include China's fiscal input, special bonds, and social capital investment.

The other important measure is inspecting water status and preventing disruption behaviours. China has flexible water scheduling according to external factors such as drought but it holds a detailed water use ledger. The head of water administration in each province is responsible for water monitoring and evaluation of its medium- and large-sized irrigation areas. During March to May each year, the heads of water administration need to submit a report to MWR's Department of Agriculture, Water Resources and Hydropower once half month. When extensive water users are spotted or potential water-stealing and water-snatch are detected, river basin authorities will have a talk with these water users, and submit an annual report to MWR's Department of Agriculture, Water Resources and Hydropower by January each year.

5.3.2 Hydroelectricity/Hydroelectric Power

Hydroelectricity is the utilisation of water flow energy to generate electricity. China's hydroelectricity, as a replacement of traditional energy sources, has soared rapidly. Hydroelectricity belongs to power/energy industry so that these projects are mainly governed by National Energy Administration. However, the utilisation of water flows directly links hydroelectricity with water-related engineering projects identified in Laws of the People's Republic of China on water (CSC, 2018). Water-related engineering projects normally relate to a river basin's water function zones, which are joint decisions made by multiple stakeholders. Considering that a river basin normally covers multiple administrative units, the river basin authorities, Department of Environmental Protection, water administrations in the provinces/autonomous regions/cities need to make zoning plans together and have them revised by all the local governments, checked by the State Council's Department of Water Administration and Department of Environmental Protection, and finally approved by the State Council.

5.3.3 Urban Water Supply

In July 1994, the State Council released the Urban Water Supply Regulations and it was amended in 2018 and 2020 respectively. Most of the information in this section was sourced from the updated regulations (GOV, 2020). Urban water includes public water supply and water supply with self-built facility. Public water supply means that urban water supply enterprises transport water resources through public water supply pipelines and their auxiliary facilities for urban activities (including production, residential living and other constructive projects). On the contrary, water supply with self-built facility indicates that urban waste use units provide water through self-built water supply pipelines and their auxiliary facilities for their own activities (including production, living and other constructive projects). However, both water suppliers have the same obligations:

- They could only start operations after they are registered with the administration for industry and commerce.
- They should establish a water quality testing system to ensure that urban water supply meets the national standards for drinking water sanitation.
- They should carry out water pressure monitoring to ensure that the pressure of water supply network meets the national standards.

- They should prohibit embezzlement or diversion of urban water supply.

Urban water supply is under the governance of China's government. Urban water supply restrictedly adheres to the borders of administrative units. The State Council establishes a specialised administrative department to take charge of national urban water supply. Provinces/autonomous regions/cities/administrative units at or above county level appoint their own administrative departments to take the responsibility for urban water supply within their respective administrative units. Moreover, pricings of urban water supply are decided by governments in provinces/cities/autonomous regions/counties but the price-making follows two principles: obtaining minimum profits for domestic/household water use, and pricing reasonably for water used for production and operation.

Speaking of domestic/household water use, drinking water is often sourced from water resources in drinking water source protection zones. All the activities that pollute water quality within the drinking water source protection zones are prohibited. In a single province/autonomous region/city/administrative unit at or above county level, protection zones should be proposed by its administrative department for urban water supply and the other relevant departments, and approved by its government. If a drinking water source protection zone is located in multiple provinces/autonomous regions/cities/administrative units at or above county level, their governments should jointly agree upon the location of drinking water source protection zone and have it approved by government at a superior level.

Chapter 6 Synergistic Development of the Beijing-Tianjin-Hebei Region to Facilitate Water Utilisation in Energy Sectors

6.1 Introduction

Examining water utilisation in energy sectors is necessary in order to achieve sustainable water resources management (C. Zhang et al., 2018). In China, electric power industry has two forms of generating electric power: hydropower (mostly seen in southern area due to its water abundance) and thermal power (typical in northern area due to its rich resources, such as coal and petroleum). Given that traditional energy resources tend to raise more environmental/water concerns, more attention should be paid to China's northern area's water inputs in energy sectors by exploring water withdrawal in the energy supply chains and analysing characteristics of water status in energy resource accumulation zones. However, few research has been conducted to investigate water-energy nexus in water footprint in China's northern area. Hence, this chapter quantifies direct and embodied water use in five energy sectors of each city in the BTH region in 2012, and analyses how synergistic development of the BTH region could facilitate the overall water utilisation of energy sectors in the region. A part of the work in this chapter has been published in Applied Energy (Li, Yang, et al., 2019).

6.2 Study Area, the Beijing-Tianjin-Hebei Region

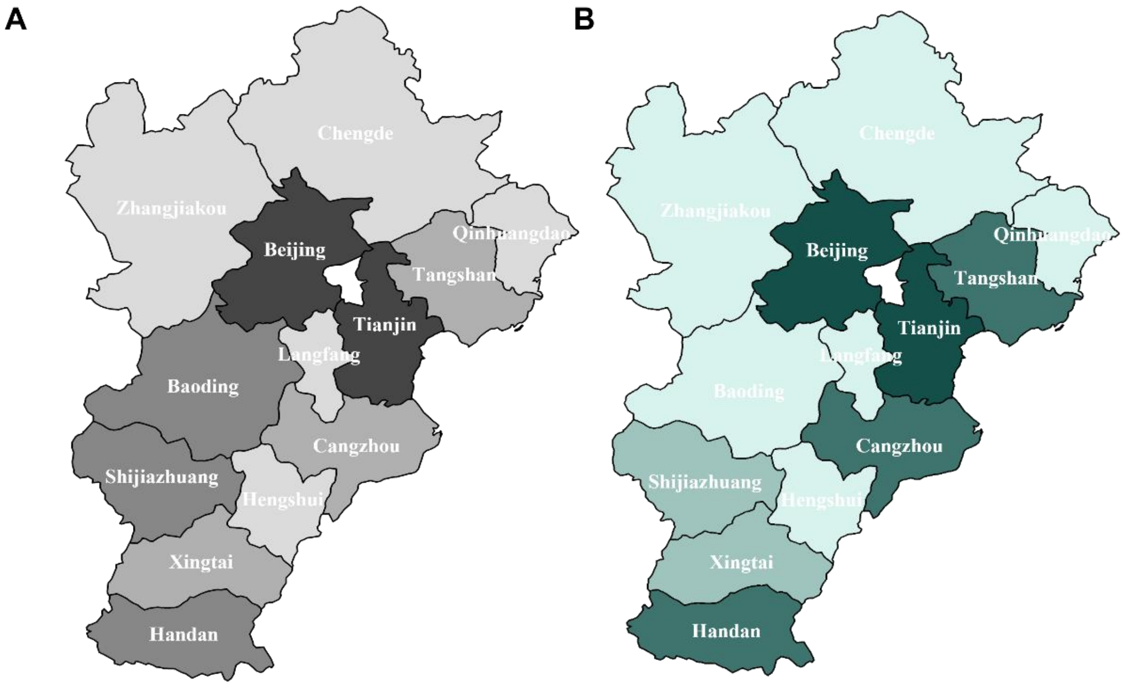

Figure 6- 1: Thirteen cities in the BTH region. (6-1A) permanent resident population in these cities: Beijing (21 million); Tianjin (14 million); Baoding (11 million); Shijiazhuang (10 million); Handan (9 million); Tangshan (8 million); Cangzhou and Xingtai (7 million); Zhangjiakou, Langfang and Hengshui (4 million); Chengde and Qinhuangdao (3 million). (6-1B) total outputs of energy sectors in these cities: Beijing (550 billion Chinese Yuan (CNY)); Tianjin (452 billion CNY); Cangzhou (171 billion CNY); Tangshan (169 billion CNY); Handan (107 billion CNY); Shijiazhuang (93 billion CNY); Xingtai (60 billion CNY); Zhangjiakou (41 billion CNY); Baoding (24 billion CNY); Langfang and Chengde (22 billion CNY); Qinhuangdao (21 billion CNY); Hengshui (19 billion CNY). Note: All the figures keep no decimal number. Note: the data for permanent resident population was sourced from China Statistic Yearbooks (NBS, 2012), and the data for total outputs of energy sectors were obtained from China's 2012 single-regional input-output tables of all the cities in the BTH.

The BTH region/Jing-Jin-Ji region is situated in North China, and Beijing is China's capital. The Chinese government has set the target of building it into 'the world-class city group as the environmental improvement demonstration region' (M. Chen et al., 2018). Therefore, the study on this region is of great significance. Figure 6-1 depicts the population distribution and total outputs of energy sectors across thirteen cities in the BTH region. Overall, the distribution of population and total outputs of energy sectors showed similar characteristics. Undoubtedly, Beijing and Tianjin had the largest population scale and overwhelming economic power as China's megacities and provincial-level municipalities. Handan's population and total outputs of energy sectors were both ranked as the fifth-largest. In contrast, the population and total outputs of energy sectors were the smallest in Langfang, Hengshui, Chengde, and Qinhuangdao. Yet differences still existed. Even though Tangshan and Cangzhou had their total outputs of energy sectors ranked as the top fourth-largest, their population was relatively small. On the contrary, a large number of population in Baoding and Shijiazhuang did not create equivalent economic gains in energy sectors.

6.3 Uneven Water Utilisation of Energy Sectors in the Beijing-Tianjin-Hebei Region

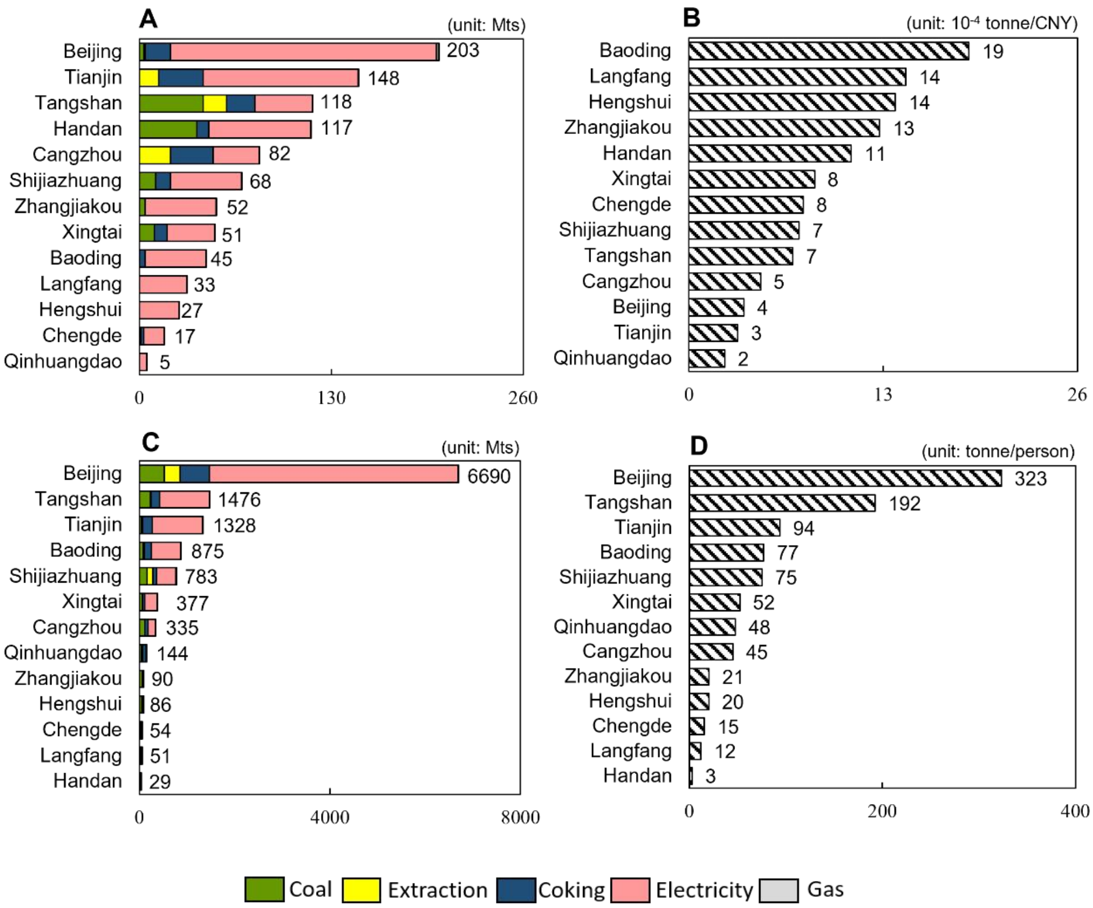

Figure 6- 2: Water utilisation of five energy sectors in the BTH region. (6-2A) direct water withdrawal in energy sectors. (6-2B) direct water intensities in energy sectors. (6-2C) embodied water withdrawal in energy sectors. (6-2D) per capita embodied water withdrawal in energy sectors. The five energy sectors are coal (coal mining), extraction (petroleum and natural gas extraction), coking (petroleum refining and coking), electricity (production and supply of electricity and heat), and gas (production and supply of gas). The unit of (6-2A) and (6-2C) is million tonnes (Mts). Note: All the figures keep no decimal number.

Figure 6-2 demonstrates the water utilisation of five energy sectors in the BTH region. Regarding direct water withdrawal in energy sectors, Beijing (203 Mts) and Tianjin (148 Mts) occupied the 1st and the 2nd largest positions, followed by Tangshan (118 Mts) and Handan. In contrast, Qinhuangdao (5 Mts) had the smallest amount. And direct water intensities can then be calculated as total direct water withdrawal divided by total output in each city's energy sectors, which implied these cities' water efficiency. Baoding (19×10^{-4} tonne/CNY), Langfang and Hengshui (14×10^{-4} tonne/CNY) were the cities with the largest direct water intensities, while Qinhuangdao (2×10^{-4} tonne/CNY) had the smallest direct water intensity, followed by Tianjin (3×10^{-4} tonne/CNY) and Beijing (4×10^{-4} tonne/CNY). The third-largest direct water withdrawer in energy sectors Tangshan had its direct water intensity ranked fifth from the bottom, at 7×10^{-4} tonne/CNY. In terms of embodied water withdrawal in energy sectors, Beijing (6690 Mts) was the largest, much larger than the 2nd and the 3rd largest cities Tangshan (1476 Mts) and Tianjin (1328 Mts). Comparatively, the amount of embodied water withdrawal in energy sectors was rather small in Handan, at 29 Mts. Meanwhile, per capita embodied water withdrawal for energy sectors can also be calculated as total embodied water withdrawal in energy sectors divided by population in each city. The per capita embodied water withdrawal in energy sectors was the largest in Beijing at 323 tonne/person, followed by Tangshan (192 tonne/person) and Tianjin (94 tonne/person). Yet Handan had the least per-capita embodied water withdrawal in energy sectors, at only 3 tonne/person. It can be observed that the rankings between embodied water withdrawal and per capita embodied water withdrawal for energy sectors only had a subtle difference, which indicated that factors such as energy demand and energy structure, rather than population, were the main factors that affected embodied water withdrawal of five energy sectors in the BTH region.

Figure 6-2 also illustrates the thirteen cities' water utilisation in five individual energy sectors. As regards the production perspective, Tangshan and Handan had the largest amounts of direct water withdrawal for coal, at 43 Mts and 39 Mts respectively, while Tianjin only withdraws 10 thousand tonnes (Kts) direct water for coal. In extraction, Cangzhou, Tangshan and Tianjin occupied the largest amounts of direct water withdrawal, at 21 Mts, 16 Mts and 13 Mts respectively, while Beijing only withdrew 1 Mt direct water in this sector. In coking, Tianjin, Cangzhou, Tangshan and Beijing had the largest amounts of direct water withdrawal, at 30 Mts, 29 Mts, 19 Mts and 17 Mts. By contrast, Qinhuangdao only had 20 Kts direct water withdrawal for coking. As for direct water withdrawal for electricity, Beijing (180 Mts) and Tianjin (105 Mts) greatly surpassed the others, especially Qinhuangdao (5 Mts), the city with the least direct water withdrawal in this sector. In gas, Beijing (2 Mts) was the largest direct water withdrawer while Zhangjiakou only withdrew 20 Kts direct water for gas. In respect of the consumption perspective, Beijing and Tangshan were ranked as the cities with the largest amounts of embodied water withdrawal for coal, at 525 Mts and 234 Mts, while Langfang only had 3 Mts embodied water withdrawal for coal. In extraction, Beijing (335 Mts) had the largest amount of embodied water withdrawal in this sector, followed by Shijiazhuang (122 Mts). Conversely, Hengshui and Chengde had small amounts of embodied water withdrawal for extraction, only at 1 Mt. In coking, the first three largest consumers of embodied water withdrawal were Beijing, Tianjin and Tangshan, at 607 Mts, 198 Mts and 181 Mts respectively, while the smallest one was Zhangjiakou, which consumed 2 Mts embodied water withdrawal in this sector. The embodied water withdrawal for electricity in Beijing (5222 Mts) greatly outweighed the other cities, even the second-largest consumer of embodied water withdrawal, Tianjin (1053 Mts). Yet Qinhuangdao only had 1 Mt embodied water withdrawal for electricity. In gas, Shijiazhuang (16 Mts) and Qinhuangdao (10 Kts) were the largest and the smallest consumers for embodied water withdrawal respectively.

Moreover, heterogeneity exited in the percentages of direct and embodied water withdrawal of individual energy sectors in that of five energy sectors across cities in the BTH region. Beijing, Tianjin and Tangshan were the largest direct water withdrawers and consumers of embodied water withdrawal in five energy sectors. Their embodied water withdrawals were mainly driven by electricity, and the percentages of embodied water withdrawal in electricity accounted for 78% (5221 Mts/6690 Mts), 79% (1053 Mts/1328 Mts) and 71% (1050 Mts/1476 Mts) respectively of the total embodied water withdrawal of energy sectors in these cities. From the production perspective, Beijing and Tianjin still occupied the largest percentages of direct water withdrawal in electricity in their total direct water withdrawal in energy sectors, at 89% (180 Mts/203 Mts) and 71% (105 Mts/148 Mts). Yet Tangshan had 36% (43 Mts/118 Mts), the largest percentage, of its total direct water withdrawal in coal.

Furthermore, the overall structure of direct and embodied water withdrawal in energy sectors can be observed in the BTH region. Electricity occupied a dominant position, with the largest amounts of direct and embodied water withdrawal in the BTH region, from both production and consumption perspectives. The total amount of direct water withdrawn for electricity in the thirteen cities took up 69% (669 Mts out of 965 Mts) of the total direct water withdrawal for energy sectors in the region, and the embodied water withdrawal in electricity accounted for 72% (8857 Mts out of 12318 Mts) of the total embodied water withdrawal for energy sectors in the region. Nevertheless, based on calculation, water efficiency in electricity was lower than that in any other energy sector. Therefore, improving water efficiency in electricity can dramatically reduce the direct water withdrawal and optimise water utilisation of energy sectors in the BTH region.

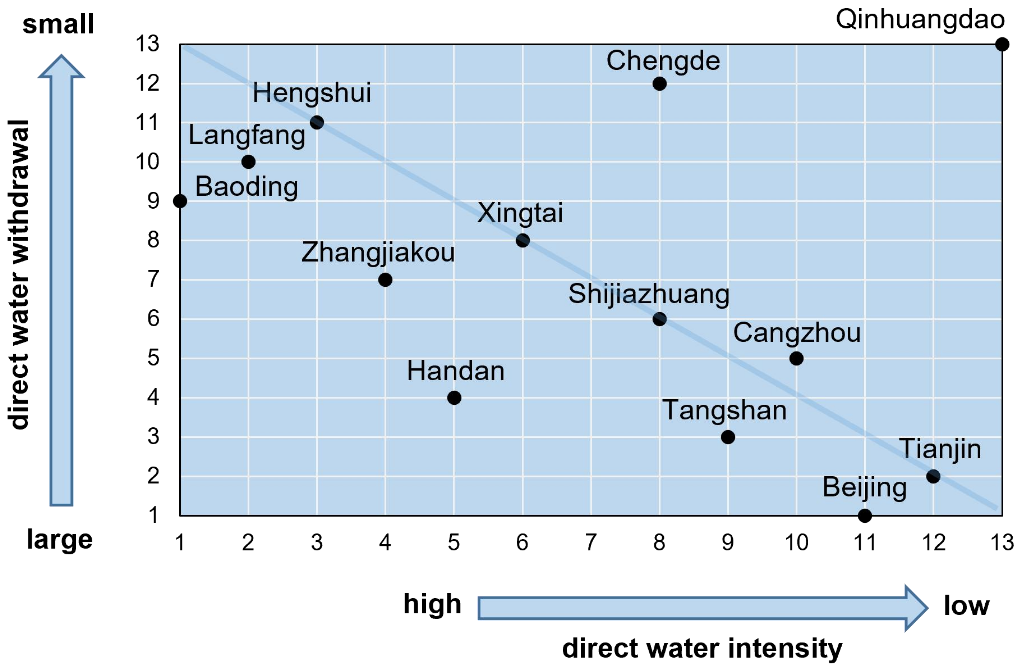

Figure 6- 3: Ranking of direct water intensity (x-axis) versus that of direct water withdrawal in five energy sectors (y-axis) across cities in the BTH region. The thirteen cities are ranked in descending order of the amounts of their direct water withdrawal and their direct water intensities. That is to say, cities with larger amounts of direct water withdrawal and direct water intensities (lower water efficiency) have higher rankings, as indicated in the arrows of this figure. The blue line in the figure divides the thirteen cities into three groups: (1) four cities on the line (cities have the same ranking of direct water withdrawal and water efficiency); (2) six cities lie below the line (cities have a higher ranking of direct water withdrawal than that of water efficiency); (3) three cities sit above the line (cities have a lower ranking of direct water withdrawal than that of water efficiency).

Figure 6-3 integrates the analysis in Section 6.3 by presenting the ranking of direct water intensity versus that of direct water withdrawal in energy sectors across cities in the BTH region. Overall, the ranking of direct water intensity versus direct water withdrawal in five energy sectors tended to present a negative correlation, which suggested that cities that withdrew more direct water in the energy sectors were inclined to have higher water efficiency.

The relationship between direct water withdrawal and water efficiency in cities with a diversity of dominant energy sectors was mainly affected by their energy structure, production scale and technology. Beijing and Tianjin had the largest amounts of direct water withdrawal, and utilised these resources most efficiently. Beijing and Tianjin's direct water withdrawal were mainly responsible for energy processing, including coking, electricity, and gas (especially electricity that can support other economic activities and be consumed by household). It was highly possible that efficient water utilisation of these energy sectors in Beijing and Tianjin was attributed by production scale that met the demand of large population size (For example, the same amount of direct water withdrawal was required to maintain the momentum of engines despite electricity generation capacity) and technological advancement catalysed by well economic development and financial support of the cities (Figure 6-1). In addition, the head of State Grid Corporation of China (SGCC) has been located in Beijing since its establishment in 2002, an enterprise that now supplies electricity to 88% of land area and to 1.1 billion citizens on national scope (SGCC, 2021). In comparison, Tangshan and Handan were energy resource-oriented cities so they actively engaged in energy resources excavation such as coal and extraction (especially coal) (GOV, 2021a). As the top direct water withdrawers for coal in the BTH region, the amount of direct water withdrawal in Tangshan (118 Mts) exceeded that in Handan (117 Mts), but water utilisation was more efficient in Tangshan (7 x 10^{-4} tonne/CNY) than in Handan (11 x 10^{-4} tonne/CNY). The reason might still lie in their difference in economy and development (Figure 6-1). Yet some cities were dominant in both energy resources excavation and energy processing. Cangzhou was the largest and the second-largest direct water withdrawer in extraction (21 Mts) and coking (29 Mts) respectively due to its abundant natural gas and petroleum resources, and its water efficiency (5 x 10^{-4} tonne/CNY) was also high, which enabled its ranking of the total output of energy sectors to reach top three in the region, at 171 billion CNY (Figure 6-1). Although Shijiazhuang (7 x 10^{-4} tonne/CNY) and Xingtai (8 x 10^{-4} tonne/CNY) had satisfactory direct water intensities, they were not as prominent as that in Cangzhou due to their water inputs in different energy supply chains for energy resources excavation (coal) and energy processing (coking).

In the cities with electricity as their dominant energy sector, the relationship between direct water withdrawal and water efficiency was solely dependent on technology, as these cities were normally not resource-endowed and thus lacked the ability to generate great profits or form economy of scale with their energy solely supplied to meet the basic demand of household. Baoding was ranked last in terms of water utilisation (19 x 10^{-4} tonne/CNY) in energy sectors, mainly in electricity, which explained the relatively low total outputs of energy sectors that were not in proportion with its population (Figure 6-1). As cities with relatively small amounts of direct water withdrawal, Qinhuangdao's (2 x 10^{-4} tonne/CNY) and Chengde's (8 x 10^{-4} tonne/CNY) direct water intensities were smaller (Qinhuangdao's direct water intensity was the smallest among thirteen cities) than those in Zhangjiakou (13 x 10^{-4} tonne/CNY), Langfang and Hengshui (14 x 10^{-4} tonne/CNY), and their dominant energy sector were all electricity.

Table 6- 1: Net water import of five energy sectors across cities in the BTH region

City	Beijing	Tangshan	Tianjin	Baoding	Shijiazhuang	Xingtai	Cangzhou
Net	6487	1358	1180	830	715	286	253
Import	Qinhuangdao	Hengshui	Zhangjiakou	Chengde	Langfang	Handan	
(Mts)	139	59	38	37	18	-88	

Note: Net water import is calculated as embodied water withdrawal minus direct water withdrawal

Statistics in Table 6-1 reveal the external dependency on water resources of five energy sectors across cities in the BTH region. Overall, the BTH region's five energy sectors were heavily reliant on water withdrawal embodied in energy-related semi- or final products of cities outside of the region, as a majority of cities in the region had positive net water import. Most of the cities with diverse dominant energy sectors tended to have larger amounts of net water import. Beijing (6487 Mts), Tangshan (1358 Mts) and Tianjin (1180 Mts) had the largest amounts of net water import, especially Beijing (nearly five times of that in Tangshan). Net water imports in Shijiazhuang (715 Mts), Xingtai (286 Mts), Cangzhou (253 Mts) were also relatively large. In order to maximise economic benefits of multiple energy sectors, these cities outsourced a part of production activities to other cities in the energy supply chain, such as manufacturing of engine components, or assembling of machinery for equipment that excavated or processed energy resources, and water withdrawal embodied in these activities were counted as their imported water. Normally, these cities further strengthened their advantageous sectors in combination with their local and imported water withdrawal, and then consumed (major cities' electricity) or exported (Tangshan's, Tianjin's and Cangzhou's extraction) the final products (Figure 6-2). On the contrary, some cities utilised imported water withdrawal to offset their energy resources insufficiency. The most obvious example was Beijing's imported water withdrawal in coal and extraction (Figure 6-2). Of thirteen cities in the BTH region, Handan was the only net water exporter (with negative net water import, at -88 Mts), and the reason lied in its export of coal and coking products, and even electricity (Figure 6-2). It was evident that water utilisation of electricity in Handan was more efficient than many other cities in the region, as it consumed less water withdrawal to serve a larger number of population (9 million, the fifth largest in the region), and still had the ability to supply electricity to other cities (Figure 6-1 and Figure 6-2).

Regarding cities with electricity as the dominant energy sector, Qinhuangdao (139 Mts), Hengshui (59 Mts), Zhangjiakou (38 Mts), Chengde (37 Mts), and Langfang (18 Mts) had relatively low net water import as their self-production and small volumes of import could satisfy their household energy consumption already, considering that they seldom exported. Even though these cities also imported water withdrawal for energy sectors other than electricity to meet the demand that could not be fulfilled previously due to the lack of energy resources (Baoding's and Hengshui's coal, Qinhuangdao's coking), the import volumes were rather small (Figure 6-2). However, Baoding's net water import (830 Mts) was ranked as the fourth largest. The main reason was that the inefficient utilisation of its local water resources led to the difficulty to sustain its energy supply at a reasonable cost without relying on the other cities.

6.4 Summary: Facilitation of Water Utilisation of Energy Sectors through Synergistic Development in the Beijing-Tianjin-Hebei Region

In the existing literature, city-level water-energy nexus footprint studies are rather limited and related studies in the current research field solely target at a single city. This case study successfully bridges this research gap by conducting the water-energy nexus footprint study in China's multiple cities for the very first time. This case study mainly investigates the uneven city-level water utilisation of five energy sectors in the thirteen cities of the BTH region and the main causes behind the phenomenon. And this case paves a pathway for the optimisation of water utilisation of energy sectors in th region through its synergistic development. Based on the analysis, the following implications are drawn:

First, synergistic development could greatly abate the effects of uneven water utilisation of electricity in the BTH region, the most prominent energy sector for both production activities and households. Electricity was essential for production activities and households in the whole region. Thus, direct and embodied water withdrawal in electricity accounted for 69% (669 Mts/965 Mts) and 72% (8857 Mts/12318 Mts) of the total direct and embodied water withdrawal in five energy sectors respectively. Yet water efficiency in this sector was comparatively low, which was made worse by the uneven water utilisation of electricity among cities in the region. In the BTH region, Baoding, Zhangjiakou, Langfang and Hengshui had relatively low water efficiency in electricity, compared with cities such as Handan, Qinhuangdao and Chengde. If each city in the region could be responsible for manufacturing or assembling of specific components for an electricity generator, a complete energy supply chain can then be formed within the region. The benefits will be threefold: (1) Cities in the region can strengthen cooperation and optimise their water utilisation with the production scale of certain semi-products. (2) Standardisation of machinery can ensure that all the cities in the region share high-quality pieces of equipment that best save water, and promote the exchange of information regarding research & development among these cities. (3) Electricity in the BTH region still heavily relied on imported water withdrawal from cities outside of the region. By this means, its external dependency of water resources can be reduced, or even turned into export if there is a product surplus.

Second, with synergistic development of the region, all the cities could fully tap the potentials of their advantageous energy sectors, and this will improve the overall water utilisation in the BTH region. In the region, cities are categorised into three types regarding their energy structures: (1) cities dominated by energy resources excavation (coal, extraction). For example, Tangshan and Handan had the edge over coal. 36% of Tangshan's direct water withdrawal was invested in coal (43 Mts/118 Mts), and its embodied water withdrawal in coal (234 Mts) was also ranked top in the region. Handan had the second-largest direct water withdrawal in coal, at 39 Mts. (2) cities dominated by energy processing (coking, electricity, gas). Given energy transformation, Beijing and Tianjin shifted their attention from conventional energy and instead occupied dominant positions in most energy processing sectors from both production and consumption perspectives. (3) cities showed strengths in both energy resources excavation and energy processing. Cangzhou's dominant energy sectors were extraction and coking. The city withdrew 21 Mts and 29 Mts direct water for the excavation and processing of petroleum and natural gas, and then ultimately exported these products. And Shijiazhuang and Xingtai had the largest direct water withdrawals in coal and coking. And synergistic development of the region could further bolster these cities' competitive energy sectors by adopting two measures: (1) enhance the cooperation among cities with similar energy structures, and probably form complete energy supply chains within these cities, as proposed earlier for electricity. (2) adjust the current energy structures. For instance, water efficiency in Shijiazhuang and Xingtai can be increased if they concentrate solely on energy excavation or energy processing. Alternatively, they can also learn from the production patterns of Cangzhou that process energy resources excavated by themselves instead of managing two different types of energy simultaneously.

Third, synergistic development requires well-developed cities to provide technological guidance towards water saving in energy sectors to the other cities in the BTH region. As discussed earlier, a city's economy and development can be a determinant factor to improve water efficiency in energy sectors. Except production scale, the other main reason is that more affluent cities can raise funds for contentious technological progress and have greater access to technology-oriented innovative pilot enterprises and leading corporates in the industry. Undoubtedly, Beijing and Tianjin were the most developed cities in the BTH region as China's megacities and provincial-level municipalities. Besides, Beijing and Tianjin had the largest direct (203 Mts and 148 Mts) and embodied (6690 Mts and 1476 Mts) water withdrawals, and the top rankings for water efficiency (4×10^{-4} tonne/CNY and 3×10^{-4} tonne/CNY). As cities with similar energy structure, Tangshan's (118 Mts) and Handan's (117 Mts) direct water withdrawals were fairly close, ranked as the third and the fourth largest in the region. Yet Tangshan's water efficiency (direct water intensity at 7×10^{-4} tonne/CNY) was higher than that in Handan (direct water intensity at 11×10^{-4} tonne/CNY), mainly due to their differences in economic strength and development level. Once synergistic development of the region is realised, a win-win situation could then be created: (1) Cities that receive technological guidance can gradually develop by learning advanced techniques to install sophisticated equipment and to minimise water use during production or maintenance, with financial subsidies of central and local governments. (2) Once the BTH region becomes an environmental demonstration region for water utilisation in energy sectors, well-developed cities can also benefit from the consolidation of the energy supply chains within the region, and the expanding influences of their advantageous energy sectors on cities outside of the region.

Chapter 7 Overall Reduction of Anthropogenic NH_4^+ Discharge Attributed by Economic Progress and Development in the Pearl River Basin

7.1 Introduction

Eutrophication has been gaining recognition as a global environmental concern in interdisciplinary (hydro-social) area (Cabello and Brugnach, 2023). Eutrophication could bring water bloom that causes a significant deterioration in water quality and toxic eutrophicated water would further compromise the original water body functions and its use for purposes in production and living, such as source of drinking water (Buta et al., 2023). As a significant change of estuarine-coastal ecosystem, eutrophication is manifested in accumulated algal blooms and widespread hypoxia in China's river basins and coastal waters, and this phenomenon is attributed by nutrient enrichment, especially excessive nitrogen under the impact of human activities (Hamilton et al., 2018; Oita et al., 2016). NH_4^+ is the predominant form of nitrogen at typical water pH and temperature, which might convert to more stable forms, nitrite nitrogen (NO_2-N) and nitrate nitrogen (NO_3-N) eventually (Schullehner et al., 2017). Therefore, it is crucial to identify the origins of anthropogenic NH_4^+ discharge to better manage water quality in upper, lower reaches of river basins, and in coastal waters. This chapter traces anthropogenic NH_4^+ discharge in the PRB in 2011 and 2017 respectively, and observes the changing patterns and reasons behind these changes. Cities covered in the PRB are shown in Table A4, including administrative units/provinces and locations in the PRB in which these cities are situated. And main industries and sectors included in this chapter can be found in Table A7.

7.2 Study Area, the Pearl River Basin

Figure 7- 1:The PRB and its watershed zones (PRD; Dongjiang; Beijing; Xijiang)

As indicated in Figure 7-1, the PRB is located in the south of China. Pearl River is the largest river in South China, with the second-largest watershed area (443 km^2) and annual runoff (338 billion m^3) in China (NBS, 2020). From 2011-2017, the eutrophication index (E) in the Pearl River estuary approximately dropped from 15 to 9, but it still confronts with the most severe eutrophication in China (E is calculated as COD x inorganic nitrogen x active phosphate x 10^6/4500) (Ministry of Ecology and Environment of the People's Republic of China (MEP), 2011-2017). In the meantime, the PRD within the PRB is now the most active economic zone in Asia & Pacific (CSC, 2021c). In 2019, the Chinese government further formulated the development plan for Guangdong-Hongkong-Macao Greater Bay Area (GBA), which would greatly stimulate the synergistic development of all the cities in the PRB in the near future (CSC, 2021d). Thus, in order to balance the economy and development, and water environment in the PRB, it is crucial to analyse the reasons behind the overall reduction of anthropogenic NH_4^+ discharge from 2011-2017.

7.3 The Overall Reduction of Anthropogenic NH_4^+ Discharge in the Pearl River Basin from 2011 to 2017

Table 7- 1: The overall trend of anthropogenic NH_4^+ discharge across industries in the PRB from 2011 to 2017

NH_4^+ Discharge (Kts)	2011	2017	Rate of Decline (%)
Total	297.32	183.28	38
Agriculture	66.55	36.35	45
Industry	26.84	15.87	41
Domestic	203.93	131.06	36
Domestic (Household)	149.91	86.77	42
Domestic (Service)	53.64	43.86	18
Domestic (Construction)	0.38	0.43	+14

Note: Domestic NH_4^+ discharge include NH_4^+ discharge in household, service and construction.

According to MEP (2011-2017), the total NH_4^+ monitored in the Pearl River estuary presented a downward trend, dropping from 35.11 Kts in 2011 to 27.37 Kts in 2017. Table 7-1 shows the overall trend of anthropogenic NH_4^+ discharge across industries in the PRB from 2011-2017. The total anthropogenic NH_4^+ discharge in the PRB corresponded with the monitoring data in the Pearl River estuary and experienced a sharp drop from 297.32 Kts to 183.28 Kts. Observed from table 7-1, domestic NH_4^+ discharge was the largest source of NH_4^+ discharge and occupied approximately 70% (203.93 Kts/297.32 Kts in 2011; 131.06 Kts/183.28 Kts in 2017) of the total NH_4^+ discharge, where around 70% (149.91 Kts/203.93 Kts in 2011; 86.77 Kts/131.06 Kts in 2017) of the domestic NH_4^+ discharge was NH_4^+ discharge in household. Agricultural and industrial NH_4^+ discharge accounted for roughly 20% (66.55 Kts/297.32 Kts in 2011; 36.35 Kts/183.28 Kts in 2017) and 9% (26.84 Kts/297.32 Kts in 2011; 15.87 Kts/183.28 Kts in 2017) of the total NH_4^+ discharge respectively. NH_4^+ discharge in construction was relatively small, at only 0.38 Kts in 2011 and 0.43 Kts in 2017. From 2011-2017, the overall reduction of NH_4^+ discharge was mainly attributed to the rapid fall in agricultural NH_4^+ discharge, NH_4^+ discharge in household, and industrial NH_4^+ discharge, by 45%, 42% and 41% respectively. Comparatively, the decline rate of NH_4^+ discharge in service was much steadier, at 18%. And NH_4^+ discharge in construction even increased by 14%.

Table 7- 2: Decrease of anthropogenic NH_4^+ discharge across industries in different watershed zones of the PRB from 2011 to 2017

NH_4^+ Discharge (Kts)	Total	Agriculture	Industry	Household	Service	Construction
Total	134.38	39.83	13.66	68.84	12.25	+0.03
The PRD	43.69	4.62	3.66	26.66	8.78	+0.03
Dongjiang	7.49	5.73	1.46	0.43	+0.13	0.01
Beijiang	26.16	12.35	2.97	8.60	2.24	0.01
Xijiang	57.04	17.14	5.56	33.15	1.35	+0.01

Note: As indicated in Table A4, cities in watershed zones might overlap. Thus, the decrease of anthropogenic NH_4^+ discharge in Table 7-2 cannot entirely match the amount in Table 7-1.

Table 7-2 presents the decrease of anthropogenic NH_4^+ discharge across industries in different watershed zones from 2011-2017. Based on the calculation, the percentages of NH_4^+ discharged by cities in Xijiang and in the PRD were the largest in the total NH_4^+ discharge of the PRB, at approximately 40% (142.42 Kts/352.23 Kts in 2011; 85.38 Kts/217.86 Kts in 2017) and 34% (118.45 Kts/352.23 Kts in 2011; 74.76 Kts/217.86 Kts in 2017) respectively. Nevertheless, the number of cities located in Xijiang (24) was far larger than that in PRD (8). According to Table7-2, the decrease of NH_4^+ discharge in Xijiang (57.04 Kts) and the PRD (43.69 kts) was most obvious, which contributed to about 75% of the reduction of total NH_4^+ discharged in the PRB altogether.

Regarding agriculture, agricultural NH_4^+ discharge reduced most in Xijiang, attributing to about 43% of the total decrease in agricultural NH_4^+ discharge in the PRB (17.14 Kts/39.83 Kts). However, the proportion of agricultural NH_4^+ discharge remained predominant, at about 29%, in the total NH_4^+ discharge in Xijiang. The reduction of agricultural NH_4^+ discharge was also relatively large in Beijiang, by 12.35 Kts. As for industry, industrial NH_4^+ discharge fell most in Xijiang (5.56 Kts) and the PRD (3.66 Kts). For household, the drop-off of NH_4^+ discharge in household was most significant in Xijiang and the PRD, which triggered over half of decrease in total NH_4^+ discharge in Xijiang (33.15 Kts/43.69 Kts) and PRD (26.66 Kts/57.04 Kts). And their reduction of NH_4^+ discharge in household took up approximately 87% (59.81 Kts/68.84 Kts) of the total decrease of household NH_4^+ discharge in the PRB. In terms of service, NH_4^+ discharge in service accounted for a larger percentage of the total NH_4^+ discharge in each watershed zone from 2011-2017: the PRD (24%-26%), Xijiang (15%-23%), Dongjiang (14%-20%), Beijiang (15%-19%), but their NH_4^+ discharge in service tended to decline. The NH_4^+ discharge in service dropped most in the PRD by 8.78 Kts, occupying roughly 72% of the reduction of total NH_4^+ discharge in service in the PRB. In contrast, NH_4^+ discharge in service rose in Dongjiang by 0.13 Kts. With regard to construction, only NH_4^+ discharge in Xijiang (0.01 Kts) and PRD (0.03 Kts) presented an upward trend.

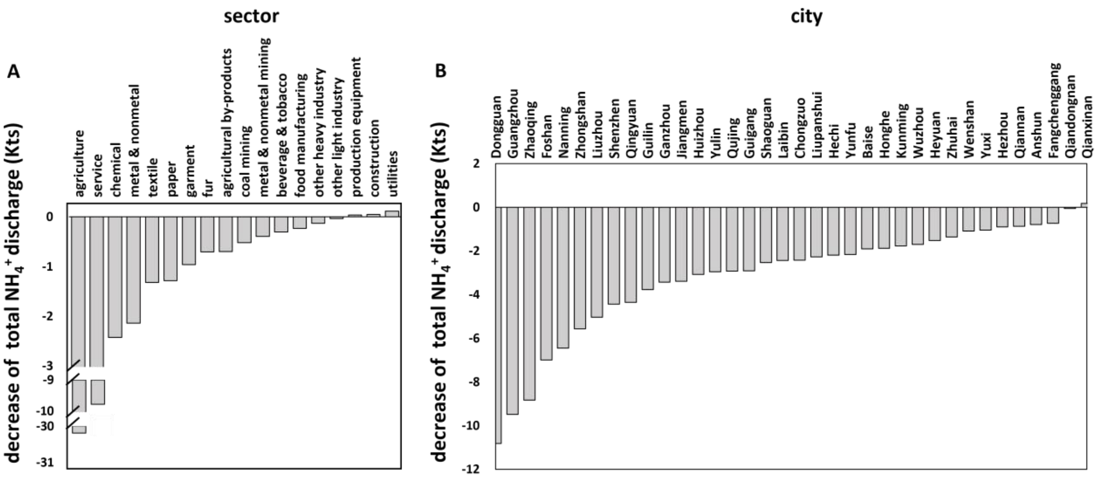

Figure 7- 2: Decrease of total anthropogenic NH_4^+ discharge across economic sectors and among cities in the PRB from 2011 to 2017. (7-2A) decrease of total anthropogenic NH_4^+ discharge in the PRB across individual economic sectors (except household). (7-2B) decrease of total anthropogenic NH_4^+ discharge among all the cities in the PRB.

Figure 7-2 identifies the main economic sectors that attributed to the overall reduction of total NH_4^+ discharge in the PRB from 2011-2017. Except agriculture, service, and construction mentioned earlier, there were industrial sectors. According to the calculation, the total NH_4^+ discharge in the PRB was split about fifty-fifty between light industry and heavy industry in 2011 (51% - 49%) and in 2017 (52% - 48%), and the decreased amounts of total NH_4^+ discharge in the PRB caused by light industry (5.52 Kts) and heavy industry (5.45 Kts) was almost equal. Seen from Figure 7-2, however, the decrease of total NH_4^+ discharge in heavy industry was solely originated from major sectors, especially chemical (2.42 Kts) and metal & nonmetal products (2.13 Kts), which fell most by the amount of NH_4^+ discharge. Coal mining (0.52 Kts) and metal & nonmetal mining (0.39 Kts) were also ranked as the top ten sectors with the most significant decrease in NH_4^+ discharge. In comparison, the decline of total NH_4^+ discharge in light industry was attributed jointly by multiple sectors, and the main sectors were ranked as textile (1.32 Kts), paper (1.28 Kts), garment (0.96 Kts), fur and agricultural by-products (0.70 Kts), beverage & tobacco (0.30 Kts), and food manufacturing (0.23 Kts) in accordance with their contributions to the overall reduction of total NH_4^+ discharge. Meanwhile, only NH_4^+ discharge in utilities (0.12 Kts) and production equipment (0.03 Kts) increased.

Figure 7-2 also illustrates the main cities in the PRB responsible for the overall reduction of total anthropogenic NH_4^+ discharge from 2011-2017. Overall, the total NH_4^+ discharge in nearly all the cities in the PRB fell, except that Qianxinan's total NH_4^+ discharge slightly increased by 0.17 Kts. Moreover, the decrease of total NH_4^+ discharge tended to be more significant for cities in lower reaches of PRB than for cities in upper reaches of the PRB. Of the top ten cities with the most obvious decrease of total NH_4^+ discharge, seven of them were even in close proximity to the Pearl River estuary. These cities were ranked in descending order as Dongguan (10.82

Kts), Guangzhou (9.48 Kts), Zhaoqing (8.84 Kts), Foshan (7.00 Kts), Zhongshan (5.57 Kts), Shenzhen (4.44 Kts) and Qingyuan (4.36 Kts).

7.4 Changes of Anthropogenic NH_4^+ Discharge across Industries and Economic Sectors at City Level in the Pearl River Basin from 2011 to 2017

A

B

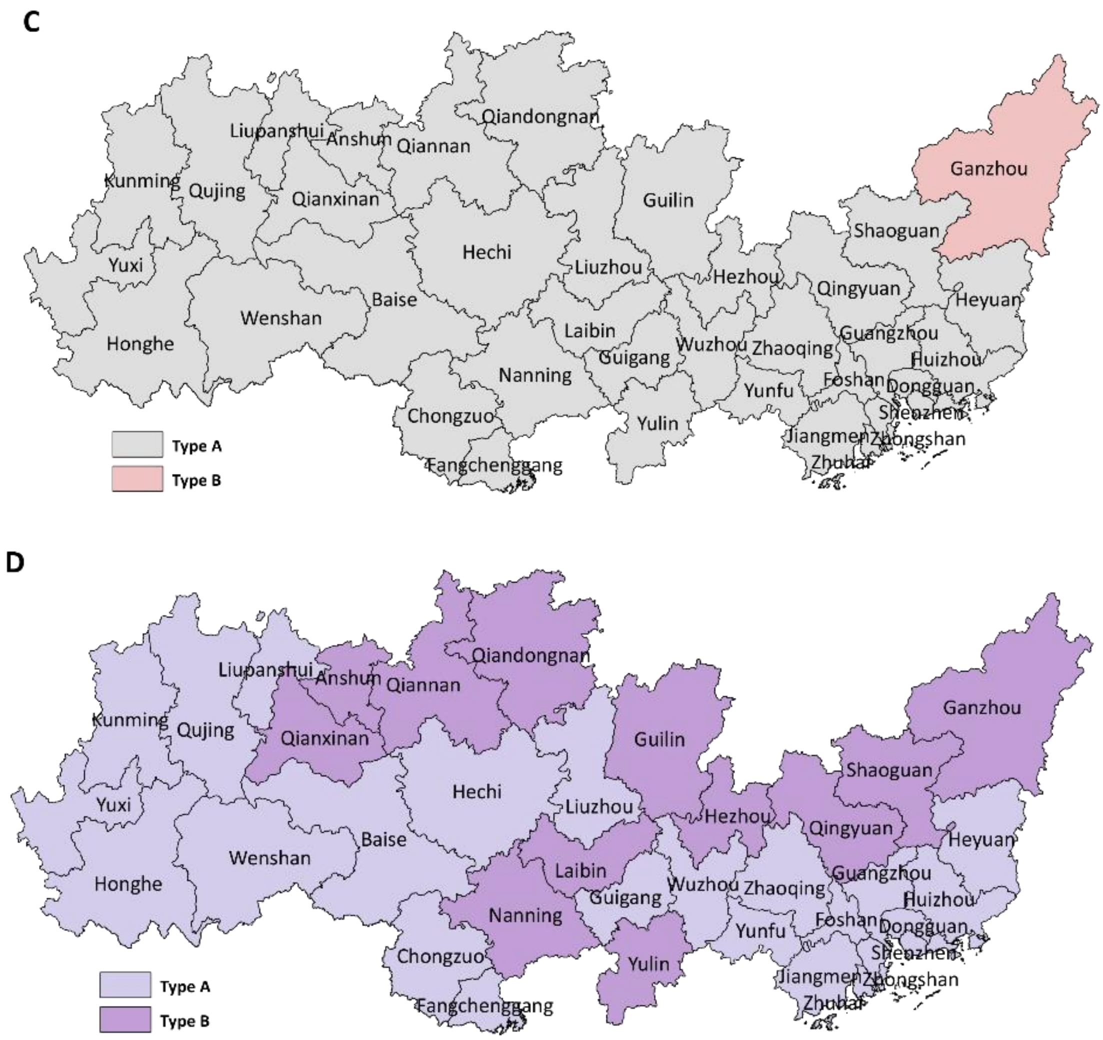

Figure 7- 3: Decrease of anthropogenic NH_4^+ discharge across industries among all the cities in the PRB from 2011 to 2017. (7-3A) decrease of agricultural NH_4^+ discharge. (7-3B) decrease of industrial NH_4^+ discharge. (7-3C) decrease of NH_4^+ discharge in household. (7-3D) decrease of NH_4^+ discharge in public service (service and construction). In this figure, Type A and Type B represent cities with a decrease and an increase in NH_4^+ discharge from 2011 to 2017 respectively.

To further investigate the reasons behind the overall reduction of anthropogenic NH_4^+ discharge in the PRB, changes of NH_4^+ discharge across industries and economic sectors at the city level in the PRB was then analysed. Figure 7-3 depicts the changes of NH_4^+ discharged across industries among all the cities in the PRB from 2011-2017.

Regarding agriculture (Figure 7-3A), NH_4^+ discharge increased in Heyuan (308 tonnes), Qiannan (237 tonnes), Qianxinan (208 tonnes), Shenzhen (70 tonnes), and Qiandongnan (15 tonnes). Shenzhen had the smallest agricultural GDP in the PRB and its agricultural GDP increased by 1.30 billion CNY. Qianxinan's, Qiandongnan's, Qiannan's and Heyuan's agricultural GDP reduced by 14.40, 11.50, 11.35, 3.01 billion CNY respectively, but these cities' agricultural NH_4^+ intensities solely decreased at a steady rate. Agricultural NH_4^+ discharge decreased in the rest of the cities, especially Ganzhou (3878 tonnes), Zhaoqing (2749 tonnes), Qingyuan (2708 tonnes), Shaoguan (2164 tonnes), and Guilin (2055 tonnes). Comparatively, the common characteristic among these cities was that the drop-off of their agricultural NH_4^+ intensities was much faster, especially in Qingyuan (26.20 x 10^{-8} tonne/CNY), Shaoguan (20.05 x 10^{-8} tonne/CNY), Ganzhou (17.43 x 10^{-8} tonne/CNY) and Zhaoqing (16.08 x 10^{-8} tonne/CNY). And Zhongshan was the only city that had negative agricultural GDP growth in the PRB, at 0.28 billion CNY. This meant that technological innovation was one of the important factors in the overall reduction of agricultural NH_4^+ discharge in the PRB.

Seen from Figure 7-3C, Ganzhou was the only city in the PRB that had increased NH_4^+ discharge in household, by 1244 tonnes, from 6193 tonnes to 7437 tonnes. Based on the calculation, all the cities in the PRB had their population soar but their per capita NH_4^+ discharge in household decline except Ganzhou, whose per capita NH_4^+ discharge in household rose from 6.74 x 10^{-4} tonne/person in 2011 to in 7.63 x 10^{-4} tonne/person in 2017. The rest of the cities had decreases in NH_4^+ discharge in household, especially in Dongguan (7408 tonnes), Guangzhou (6997 tonnes), Nanning (4559 tonnes), Zhaoqing (4252 tonnes), Zhongshan (3370 tonnes) and Shenzhen (3137 tonnes). Even though the population increases were the largest in Shenzhen (2.06 million persons) and Guangzhou (1.75 million persons), the decreases of per capita NH_4^+ discharge were more obviously seen in cities with relatively small population, especially in Zhaoqing (11.06 x 10^{-4} tonne/person), Zhongshan (10.93 x 10^{-4} tonne/person) and Dongguan (x 10^{-4} tonne/person). These points indicated that the improvement of environmental awareness of residents might be the key leading to the overall reduction of NH_4^+ discharge in household in the PRB.

Observed from Figure 7-3D, the largest number of cities had an increase in NH_4^+ discharged by public service, mainly by service, given the small amount of NH_4^+ discharge in construction. Of 36 cities in the PRB, one-third of them had increased NH_4^+ discharge in service, especially Qiandongnan (487 tonnes), Ganzhou (450 tonnes), Qingyuan (392 tonnes), Hezhou (165 tonnes), Guilin (160 tonnes), Yuli (151 tonnes), Laibin (106 tonnes). And 22 cities' NH_4^+ discharge in construction increased, especially Hechi (22 tonnes), Shenzhen (20 tonnes), Zhuhai and Dongguan (13 tonnes). In contrast, cities with the largest decreased amounts of NH_4^+ discharge in service were Dongguan (2132 tonnes), Foshan (1732 tonnes), Shenzhen (1526 tonnes), Zhaoqing (1449 tonnes), Zhongshan (1305 tonnes), and Guangzhou (1167 tonnes). Zhuhai, Laibin and Ganzhou dropped most in NH_4^+ discharged by construction, by 22, 11 and 10 tonnes respectively. In the PRB, GDP of construction and of service in all the cities skyrocketed. And it was found that cities with decreased NH_4^+ discharge in public service had the greatest GDP growth in public service, and/or experienced the sharpest declines in NH_4^+ intensity for public service in the PRB. Zhaoqing's, Zhongshan's, Dongguan's and Foshan's decreases of NH_4^+ intensities in service were rather obvious, by 3.52 x 10^{-8}, 2.45 x 10^{-8}, 1.61 x 10^{-8}, 1.24 x 10^{-8} tonne/CNY. Comparatively, Guangzhou (762.98 billion CNY) and Shenzhen (699.67 billion CNY) were predominant in terms of GDP growth in service in the PRB, but the decreases of their NH_4^+ intensities in service were far lower, at 0.41 x 10^{-8} and 0.54 x 10^{-8} tonne/CNY. Zhuhai (11.41 billion CNY) and Ganzhou (8.55 billion CNY) had the largest GDP growth in construction, and Laibin's decrease of NH_4^+ intensities in construction (0.35 x 10^{-8} tonne/CNY) was the largest in the PRB. On the contrary, GDP of service and construction in cities that had an increase of NH_4^+ discharge in public service grew at a steadier rate, and their NH_4^+ intensities in public service also fell in a smaller range. However, some cities still had increased NH_4^+ intensities in service (Qingyuan) and in construction (Hechi, Shenzhen, Shaoguan, Zhaoqing, Dongguan, Huizhou). These points implied that the overall reduction of NH_4^+ discharge in public service was influenced both by the development speed of the tertiary industry and the overall technological development in the tertiary industry.

It can be seen from Figure 7-3B, Wuzhou (257 tonnes), Qianxinan (156 tonnes), Shenzhen (129 tonnes), Qiandongnan (107 tonnes), and Anshun (35 tonnes) had increased industrial NH_4^+ discharge. In contrast, the declines of industrial NH_4^+ discharge were most obvious in Liuzhou (1362 tonnes), Ganzhou (1236 tonnes), Dongguan (1057 tonnes), Foshan (1029 tonnes), Laibin (698 tonnes), Nanning (625 tonnes), Jiangmen (494 tonnes), Zhuhai (456 tonnes), Qujing (450 tonnes), Zhongshan (441 tonnes). Given the diversity of industrial sectors, the reasons triggered these changes were further explained in Figure 7-4.

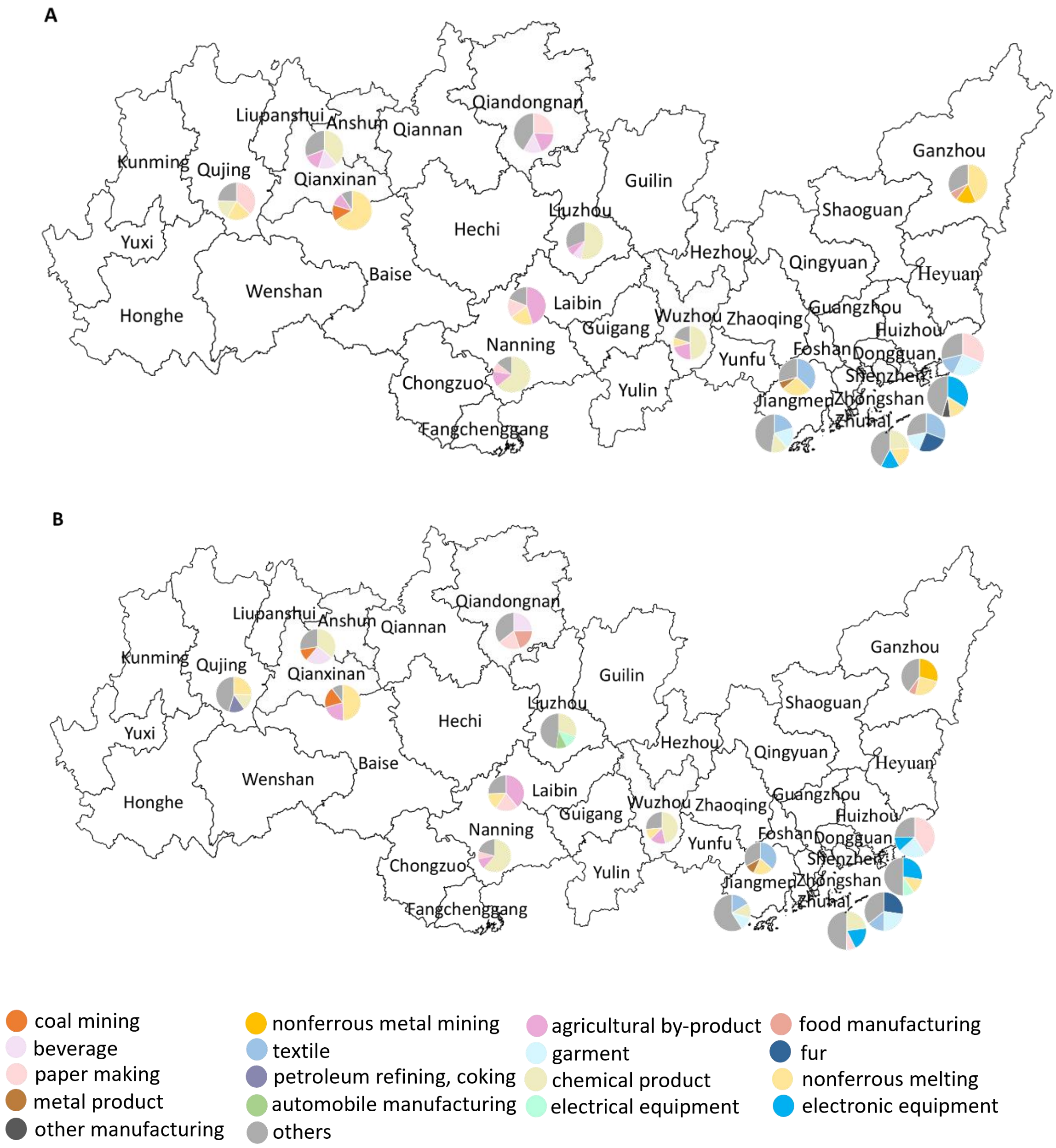

Figure 7- 4: Changes of industrial NH_4^+ structures of cities in the PRB with the most significant increases/decreases in industrial NH_4^+ discharge from 2011 to 2017. (7-4A) industrial NH_4^+ structure in 2011. (7-4B) industrial NH_4^+ structure in 2017. To ensure a clear view in this figure, each city only shows its top 3 industrial sectors with the largest NH_4^+ discharge, and NH_4^+ discharged by the rest of industrial sectors are categorised into others.

Figure 7-4 demonstrates the changes of industrial NH_4^+ structures in cities with the most obvious NH_4^+ discharge increases/decreases in the PRB from 2011-2017. There were two types of cities. Obvious changes of industrial NH_4^+ structures were seen in the first type of cities. For cities with increases in industrial NH_4^+ discharge, one of their major NH_4^+ discharge-intensive industrial sectors were replaced by another less NH_4^+ discharge-intensive sectors instead, and these cities were Liuzhou (from food manufacturing to electrical equipment and transport equipment), Dongguan (from textile to communication device), Qujing (from paper making to petroleum coking) and Zhuhai (from nonferrous melting to paper making). As the only city fitted into the first type and at the same time had decreases in industrial NH_4^+ discharge, Anshun's food manufacturing was taken over by coal mining, whose NH_4^+ intensity was lower than that in food manufacturing.

Regarding the second type of cities, their NH_4^+ structures barely changed, but their increases/decreases in industrial NH_4^+ discharge were still significant. Increased industrial NH_4^+ discharges in Wuzhou (chemical product (106 tonnes/257 tonnes), nonferrous melting (39 tonnes/257 tonnes), Qianxinan (agricultural by-product (57 tonnes/156 tonnes), coal mining (43 tonnes/156 tonnes), nonferrous melting (38 tonnes/156 tonnes)), Shenzhen (communication device (101 tonnes/129 tonnes)), and Qiandongnan (food manufacturing (57 tonnes/106 tonnes), beverage (44 tonnes/106 tonnes)) were mainly attributed by the discharges of their major industrial sectors. And the decreases of industrial NH_4^+ discharge in Ganzhou (nonferrous melting (671 tonnes/1236 tonnes), nonferrous metal mining (119 tonnes/1236 tonnes)), Foshan (textile (387 tonnes/1029 tonnes), nonferrous melting (337 tonnes/1029 tonnes)), Laibin (agricultural by-product (332 tonnes/698 tonnes), nonferrous melting (152 tonnes/698 tonnes), paper making (101/698 tonnes)), Nanning (chemical product (419 tonnes/625 tonnes), agricultural by-product (116 tonnes/625 tonnes)), Jiangmen (garment (150 tonnes/493 tonnes), textile (138 tonnes/493 tonnes)) and Zhongshan (textile (211 tonnes/441 tonnes), fur (125 tonnes/441 tonnes)) were also impacted by the discharges of their dominant industrial sectors. However, a majority of the above-mentioned cities' industrial sectors' NH_4^+ intensities declined (except Qianxinan's coal mining and agricultural by-product, Zhongshan's textile and fur). This signified that the decreases in industrial NH_4^+ discharge of cities in the PRB were closely associated with the reduction of NH_4^+ intensities of their industrial sectors, while the increased industrial NH_4^+ discharges of cities in the PRB were mainly driven by the rapid growth of their industrial sectors.

7.5 Summary: Economic Progress and Development Impacted Greatly on the Overall Reduction of Anthropogenic NH_4^+ discharge in the Pearl River Basin

In the current research filed, studies that probe into the effects of water pollutants triggered by human activities on river basins often apply watershed models, but the models cannot identify water pollutants from specific administrative units, not to mention specific economic sectors. This case study therefore fills this research gap by tracing the anthropogenic sources of water pollutants discharged by all the cities in the PRB. This case study mainly examines how economic progress and development led to the overall reduction of anthropogenic NH_4^+ discharge in the PRB from

2011-2017 by first identifying the anthropogenic sources of NH_4^+ discharge across industries and economic sectors at the city level in the PRB, and then analysing the key characteristics of main cities with increases/decreases of NH_4^+ discharge in the PRB. According to the analysis, the overall anthropogenic NH_4^+ discharge in the PRB was reduced with the following approaches:

First, more focuses were placed on agriculture, household and industry (especially critical heavy industrial sectors) because they contributed the most to the overall reduction of anthropogenic NH_4^+ discharge. The NH_4^+ discharge in the PRB declined by 45% (66.55-36.35 Kts), 42% (149.91-86.77 Kts) and 41% (26.84-15.87 Kts) in agriculture, household and industry respectively. NH_4^+ discharges in service and construction were relatively small, and NH_4^+ discharge reduced by 18% for service but increased by 14% for construction. Meanwhile, reduction of industrial NH_4^+ discharge in the PRB was contributed by major heavy industrial sectors especially chemical (2.42 Kts) and metal & nonmetal products (2.13 Kts), and jointly by multiple light industrial sectors with top 3 dischargers as textile (1.32 Kts), paper (1.28 Kts) and garment (0.96 Kts).

Second, the PRD was identified as a critical area in the PRB as its impacts on the overall reduction of anthropogenic NH_4^+ discharge in the PRB and on the offshore environment in the Pearl River estuary were the greatest. Even though Xijiang and the PRD accounted for approximately 40% (142.42 Kts/352.23 Kts in 2011; 85.38 Kts/217.86 Kts in 2017) and 34% (118.45 Kts/352.23 Kts in 2011; 74.76 Kts/217.86 Kts in 2017) of the total reduction of NH_4^+ discharge in the PRB respectively, the PRD only had 8 cities while Xijiang covered 24 cities. And of the top 10 cities attributed to the most decreases of NH_4^+ discharge in the PRB, seven of them were located in or close to the PRD: Dongguan (10.82 Kts), Guangzhou (9.48 Kts), Zhaoqing (8.84 Kts), Foshan (7.00 Kts), Zhongshan (5.57 Kts), Shenzhen (4.44 Kts) and Qingyuan (4.36 Kts). These discharges directly affected the total NH_4^+ monitored in the Pearl River estuary (35.11 Kts in 2011 to 27.37 Kts in 2017) due to their proximity to coastal water. It was because that in the PRB, the PRD is the most economically dynamic and densely populated region. Compared with the other regions in the PRB, the PRD itself formed an independent and mature economy and cultivated industry leaders that abated NH_4^+ pollution in the PRB, such as Zhaoqing's and Qingyuan's agriculture, Dongguan's, Foshan's industry, and Shenzhen's service. Besides, the PRD attracted about 54% of the population in the PRB, and thus its fall of NH_4^+ discharge in household was relatively obvious (NBS, 2011-2015).

Third, environmental consciousness was strengthened among residents, which might to be a critical factor to the overall reduction of NH_4^+ discharge in household in the PRB. In the PRB, almost all the cities had their population grow but NH_4^+ discharge in household decline. Ganzhou was the only city that had increased NH_4^+ discharge (6193-7437 tonnes) and per capita NH_4^+ discharge (6.74×10^{-4}-7.63×10^{-4} tonne/person) in household. Besides, in some well-developed cities such as Shenzhen and Guangzhou, per capita NH_4^+ discharges tended to be stagnant after a period of time. It was probably because residents in these cities had environmental awareness in the first place, but they were unwilling to further lower the standard with higher incomes and the pursuit of better life quality.

Fourth, the transformation of economic structure and technological advancement benefited the overall reduction of NH_4^+ discharge of economic sectors (except household) in the PRB. For agriculture and public service, NH_4^+ discharge tended to drop in cities that had the sharpest decreases in agricultural NH_4^+ intensities (Ganzhou, Zhaoqing, Qingyuan and Shaoguan) and NH_4^+ intensities in service (Dongguan, Foshan, Zhaoqing and Zhongshan) and NH_4^+ intensities in construction (Zhuhai, Laibin and Ganzhou). However, their difference was that cities with decreases in agricultural NH_4^+ discharge and NH_4^+ discharge in public service were inclined to undergo steady and dramatic GDP growth respectively. This was most likely because increase/decrease of agricultural NH_4^+ pollution was in proportion with growing/shrinking agricultural product demand. Instead, both NH_4^+ discharge and NH_4^+ intensity in public service inclined to be more stable once economic scale was formed to generate high value-added long-term yields, such as in well-developed cities Guangzhou and Shenzhen. Regarding industry, cities with decreased NH_4^+ discharge either saw obvious industrial NH_4^+ structure transformation (An Anshun's major industrial sector was transferred from food manufacturing to coal mining), or had the sharpest drop of industrial NH_4^+ intensities in their major industrial sectors (such as Ganzhou's and Foshan's nonferrous melting, Nanning's chemical product, Foshan's and Zhongshan's textile, and Laibin's agricultural by-product).

Fifth, however, greater attention should be paid to cities that caused increases in NH_4^+ discharge from different anthropogenic sources in order to further reduce NH_4^+ discharge in the PRB, such as agriculture in Heyuan (308 tonnes), Qiannan (237 tonnes) and Qianxinan (208 tonnes), household in Ganzhou (1224 tonnes), service in Qiandongnan (487 tonnes) and Ganzhou (450 tonnes), construction in Hechi (22 tonnes) and Shenzhen (20 tonnes), as well as Wuzhou's chemical product (106 tonnes), Shenzhen's communication device (101 tonnes), Qianxinan's agricultural by-product and Qiandongnan's food manufacturing (57 tonnes).

Chapter 8 Economic Trade Exacerbates Water Imbalance in China’s 313 Cities

8.1 Introduction

Virtual water can balance the supply and demand of water resources in regions suffering from water scarcity via commercial trade (Zhao et al., 2020). Therefore, the link between water scarcity and virtual water flows embodied in economic trade need to be established to deepen the understanding of water resources optimisation. In the current research field, researchers have associated water scarcity with virtual water flows in China, but solely at the provincial level (Feng et al., 2014; Zhao et al., 2018). Relevant studies at city level were still poorly understood. Thus, This chapter first analyses the water stress and accounts virtual water flows of China’s 313 cities in 2015, followed by emphasising how economic trade triggers water imbalance, especially in water-scarce cities. In this chapter, administrative units (written as 313 cities in this chapter for simplicity) and economic sectors targeted in this research can be seen in Table A6 and Table A8 respectively.

8.2 Water Stress in China’s Cities

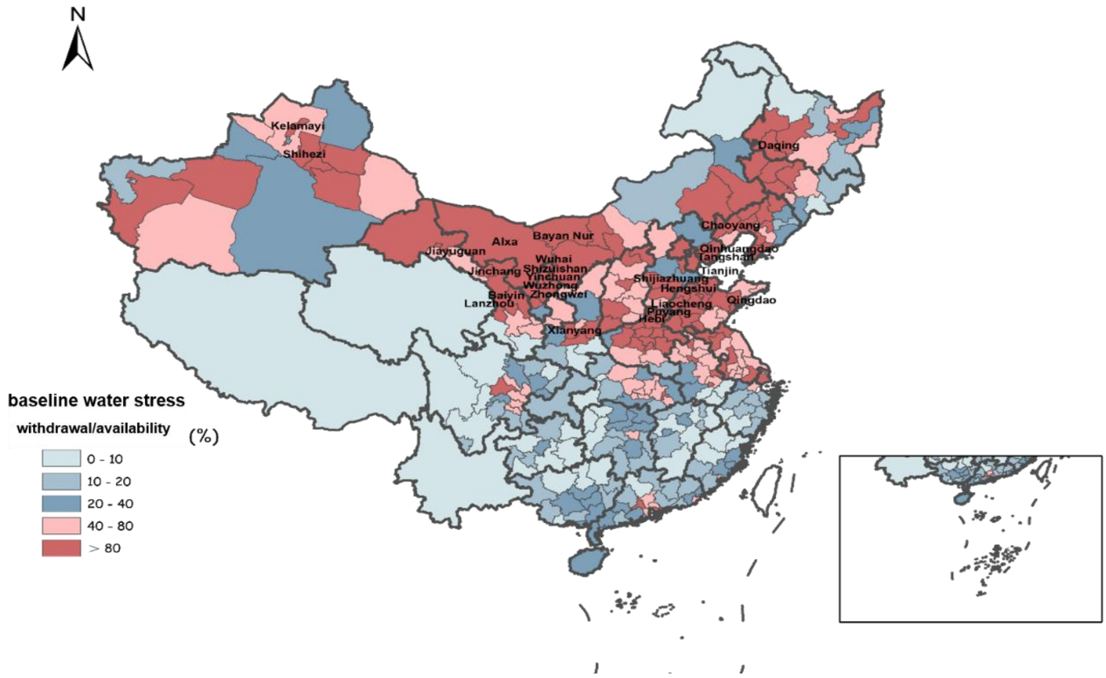

Figure 8- 1: Water stress in 313 Chinese cities. Water stress is defined as the total water withdrawal as a percent of the total annual water availability, or the water withdrawal-to-water availability ratio. The greater the criticality ratio is, more severe water stress a city faces (Classification: 0%-10% (no water stress); 10%-20% (low water stress); 20%-40% (moderate water stress); 40%-80% (serious water stress); >80% (severe water stress), where serious and severe waters stress are considered as tricker water issue) (World Resources Institute (WRI), 2017). Note: the date for water availability were partly sourced from China Statistic Yearbooks and then further compiled by Z. Zhang et al. (2020).

Figure 8-1 presents the water status of Chinese cities, which showcases geographical differences. Cities stricken by water shortage were mostly located in Northwest China (Xinjiang, Gansu, Shaanxi), in Northeast China (Heilongjiang, Liaoning, Jilin), in North China (Inner Mongolia, Jing-Jin-Ji region, Shanxi), in the north of Central China (Henan) and East China (Shandong, Anhui, Jiangsu, Shanghai). In contrast, most of the cities in Southwest China and South China did not hit worrisome levels regrading water stress, except Chengdu, Ezhou, Foshan and Shenzhen. Of 313 cities, roughly 32% of them (101 cities) suffered from severe water stress. Top water-scarce cities, led by Shihezi (3857%), Jiayuguan (3507%), Wuzhong (1516%), Yinchuan (1331%), Bayan Nur (1106%), had criticality ratios far greater than 80%. Almost half of the cities (168/313 cities) were confronted with serious or severe water stress, as highlighted in red in the figure.

8.3 Virtual Water Flows among China's Main Regions and Cities

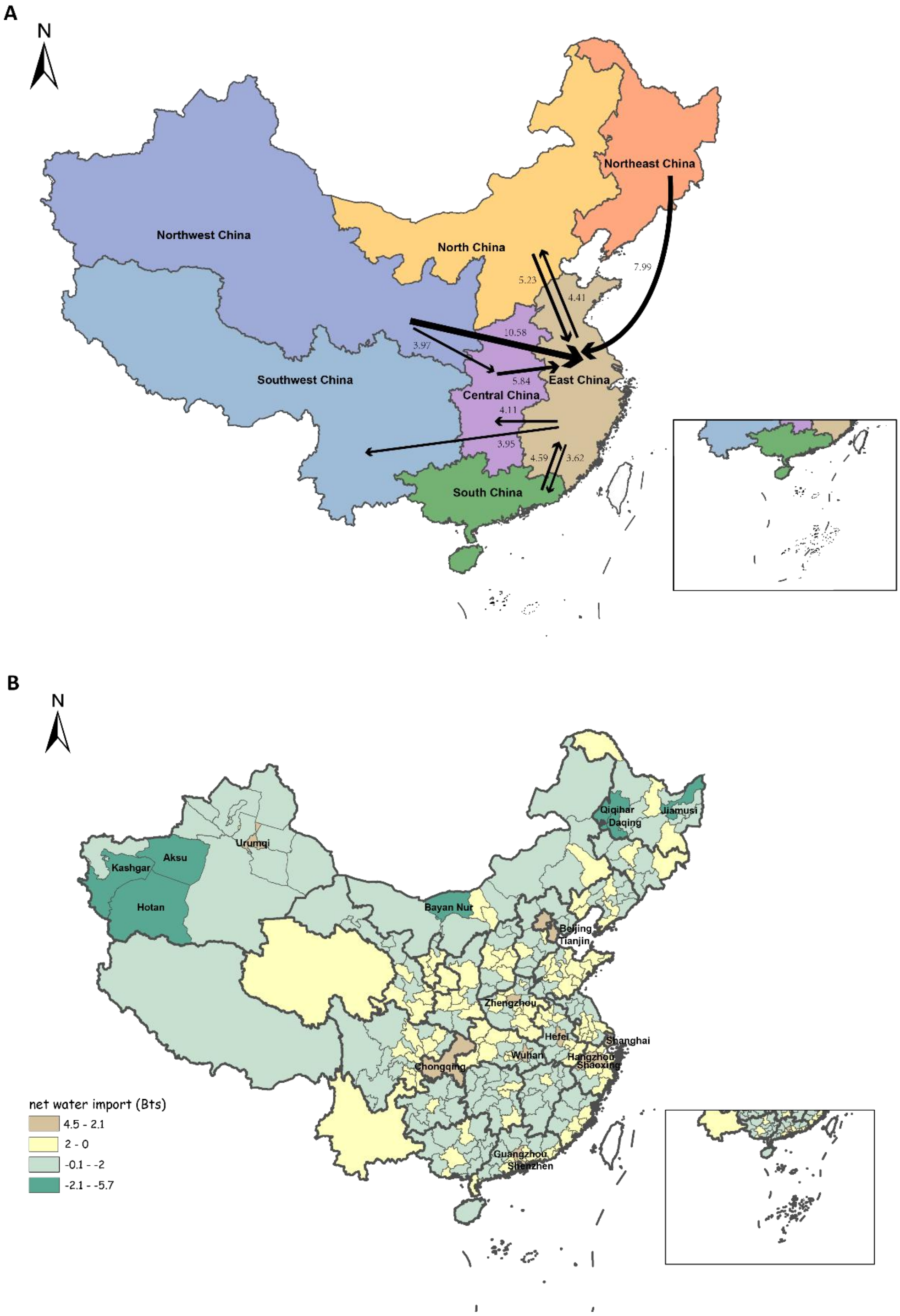

Figure 8- 2: China's virtual water flows. (8-2A) virtual water flows among China's seven regions. The unit of virtual water flows is billion tonnes (Bts). (8-2B) net water import of 313 Chinese cities. Net water import is calculated as water inflow minus water outflow in a city. Negative net water import equals to net water export. Cities with positive/negative net water import is defined as water importer/exporter. Note: The regional division of 313 Chinese cities can be accessed in Table A6.

Figure 8-2 demonstrates the virtual water flows among the main regions in China. East China imported virtual water from all the regions, especially from Northwest China (10.58 Bts) and Northeast China (7.99 Bts). East China, in the meantime, exported virtual water to other regions, such as North China (4.41 Bts), Central China (4.11 Bts) and Southwest China (3.95 Bts). Of the top 10 virtual water flows with the largest volume, 3.97 Bts of virtual water was also transferred from Northwest China to Central China. Figure 8-2 also exhibits the water flows among Chinese cities. Given the complexity of virtual water trade at the city level, net water import is shown. The largest water exporters (net water export > 2 Bts) were only located in Xinjiang, Inner Mongolia, and Heilongjiang province. These 7 cities, sorted by value in descending order, were Kashgar (5.7 Bts), Aksu (4.7 Bts), Banyan Nur (3.1 Bts), Qiqihar (2.7 Bts), Hotan (2.4 Bts), Daqing and Jiamusi (2.2 Bts). In comparison, the largest water importers (net water import > 2 Bts) were widely dispersed and covered all the regions except Northeast China. Similarly, these 12 cities can be arranged by value in descending order as: Beijing (4.4 Bts), Chongqing and Guangzhou (3.9 Bts), Tianjin (3.5 Bts), and Urumqi, Hefei, Shaoxing, Wuhan, Shenzhen, Shanghai, Zhengzhou, Hangzhou, whose net water import falls between 2 and 3 Bts.

To sum up, the largest volume of virtual water outflows were from Northwest China and Northeast China, in which the main exporters were Kashgar, Aksu and Hotan in Northwest China, Qiqihar, Daqing and Jiamusi in Northeast China. As the largest virtual water inflow regions, East China's main importers included Hefei, Shaoxing, Shanghai, Hangzhou, and Central China's main importers were Zhengzhou and Wuhan. The other major water exporter was Bayan Nur in Inner Mongolia, North China, and the rest of the water importers were Beijing, Tianjin in North China, Chongqing in Southwest China, Guangzhou, and Shenzhen in South China.

8.4 Imbalanced Water Stress and Virtual Water Flows Embodied in Trade

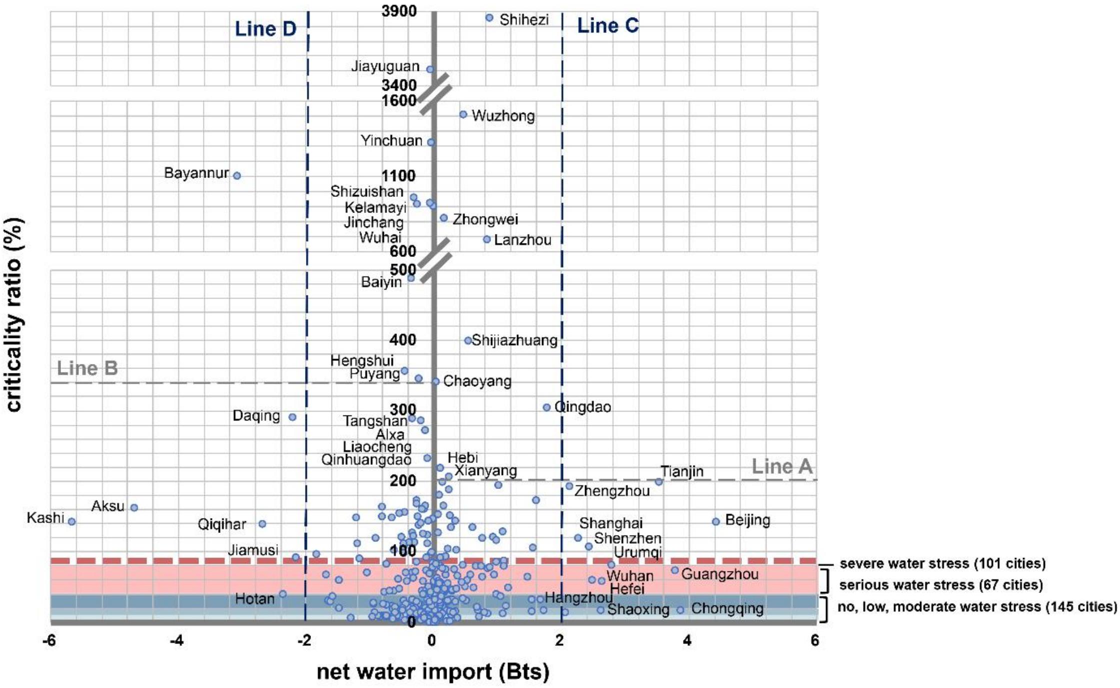

Figure 8- 3: Net water import (x-axis) versus criticality ratio (y-axis) of 313 Chinese cities. Above Line A/Line B are the top 10 water importers/exporters with the largest criticality ratios. Cities with net water import/export larger than 2 Bts lie on the right/left of line C/line D.

Table 8- 1: Supporting statistics related to Figure 8- 3

	Number of City	Water Importer	Water Exporter	Ratio
In Total	313	138	175	44-56
A. No Water Stress	43	13 (9%)	30 (17%)	30-70
B. Low Water Stress	52	20 (14%)	32 (18%)	38-62
C. Moderate Water Stress	50	20 (14%)	30 (17%)	40-60
D. Serious Water Stress	67	41 (30%)	26 (15%)	61-39
E. Severe Water Stress	101	44 (32%)	57 (33%)	44-56

Note: The parenthesis in column Water Importer and Water Exporter indicates the percentage of water-imported/-exported cities with water stress at a specific level in the total number of water importers/exporters. Column Ratio presents the weight of water importers and exporters at certain water stress levels.

Figure 8-3 depicts the imbalanced relationship between water stress and virtual water flows among Chinese cities, and supporting statistics are in Table 8-1 Overall, water exporters outweighed water importers, either for all the cities or for cities whose water flow larger than 2 Bts. And the number of water exporters with severe water stress were larger than those for water importers. Criticality ratios in the top 10 water exporters were over 340% (see line B) whereas those in the top 10 water importers were much lower, at around 200% (see line A). A similar conclusion also suited at least the top 15 water exporters and importers. Nevertheless, the percentage of water importers with serious or even more critical water stress (62%; 85/138) was larger than those in water exporters (47%; 83/175). Correspondingly, 38% and 53% of water importers and exporters experienced moderate or milder water stress. As indicated in the figure, there were main water exporters with large criticality ratios, those with criticality ratio over 200%, or those fell in the negative x axis ranging from 2 to 6 Bts, or Bayan Nur which matched both criteria. Except Hotan, the largest water exporters (net water export > 2 Bts) all had their criticality ratios lie above the threshold for severe water stress. On the contrary, only the five largest water importers (net water import > 2 Bts) were beyond this limit.

Table 8- 2: Top water exporters (net water export > 2 Bts) and their total and agricultural water intensities, and top 10 cities where their virtual water exported to.

	Water Intensity (10^{-4} tonne/CNY)	Agricultural Water Intensity (10^{-4} tonne/CNY)	Top 10 Cities
Kashi	712	2138	Urumqi, Changji, Bayingol, Aksu, Ili, Shihezi, Tianjin, Chongqing, Tarbagatay, Beijing
Aksu	791	3019	Urumqi, Changji, Bayingol, Kashi, Ili, Shihezi, Tianjin, Chongqing, Tarbagatay, Beijing
Bayannur	282	1543	Hohhot, Baotou, Hulun Buir, Ordos, Beijing, Chongqing, Shanghai, Tianjin, Tongliao, Chifeng
Qiqihar	246	1057	Harbin, Suihua, Tianjin, Chongqing, Daqing, Beijing, Shanghai, Guangzhou, Mudanjiang, Yichun
Hotan	1050	3054	Urumqi, Changji, Bayingol, Kashi, Aksu, Tianjin, Ili, Shihezi, Chongqing, Tarbagatay
Daqing	104	1228	Harbin, Chongqing, Shanghai, Tianjin, Jiamusi, Suihua, Qiqihar, Beijing, Yichun, Mudanjiang
Jiamusi	259	917	Harbin, Tianjin, Suihua, Qiqihar, Chongqing, Daqing, Beijing, Shanghai, Guangzhou, Mudanjiang

Note: 313 cities: average water intensity (57×10^{-4} tonne/CNY); average agricultural intensity (434×10^{-4} tonne/CNY)

Water Importers: average water intensity (18×10^{-4} tonne/CNY); average agricultural intensity (245×10^{-4} tonne/CNY)

Water Exporters: average water intensity (88×10^{-4} tonne/CNY); average agricultural water intensity (584×10^{-4} tonne/CNY)

In Table 8-2, water intensity denotes the amount of water withdrawn to generate per unit product output. In general, water exporters needed to exploit more local water resources than water importers for one unit of output, especially for the top water exporters, whose water intensities greatly exceeded the average water intensity either for 313 cities or for all the water exporters. Furthermore, agriculture was highly water consuming. At the national level, 75% of direct water was devoted to agriculture. Far beyond the national standard, the top water exporters had over 95%

of their direct water in agriculture, except Daqing (80%). However, it is obvious that agricultural water intensity greatly outweighed the overall water intensity, not to mention those for the top water exporters. Table 8-2 also lists the top 10 cities to which each top water exporter transferred their virtual water respectively. Except cities in the same province, China's earliest megacities were targeted as well (Beijing, Tianjin, Chongqing, Shanghai, Guangzhou).

Table 8- 3: Virtual water flows across agriculture, industry, and service among China's seven regions.

(Unit: Bts)	Virtual Water Inflows				Virtual Water Outflows			
	Total	Agri.	Indus.	Service	Total	Agri.	Indus.	Service
North China	15.5	0.9	10.2	4.4	11.4	8.8	2.3	0.3
Northeast China	6.3	0.7	3.9	1.7	19.2	16.8	2.2	0.2
Northwest China	5.7	0.4	3.7	1.6	25.1	23.5	1.6	0.1
East China	37.5	1.8	29.7	6.0	20.5	11.7	8.2	0.5
Central China	16.1	1.0	12.8	2.3	13.5	8.2	5.1	0.2
South China	14.3	1.5	9.1	3.7	10.5	7.3	3.0	0.3
Southwest China	12.5	1.0	8.8	2.7	7.8	4.5	3.0	0.2

Note: Agri. and Indus. stand for Agriculture and Industry respectively.

Following Figure 8-2, Table 8-3 furthermore showcases virtual water flows across industries among China's seven regions. For agriculture, Northwest China's and Northeast China's virtual water outflows were ranked as the largest and the second largest, while regions with the largest volume of virtual water inflows were East China and South China. In terms of industry, East China and Central China occupied a dominant position for virtual water inflows and outflows, and the water inflow to East China doubled that to Central China. Regarding service, East China was the largest virtual water importer and exporter, followed by North China and South China.

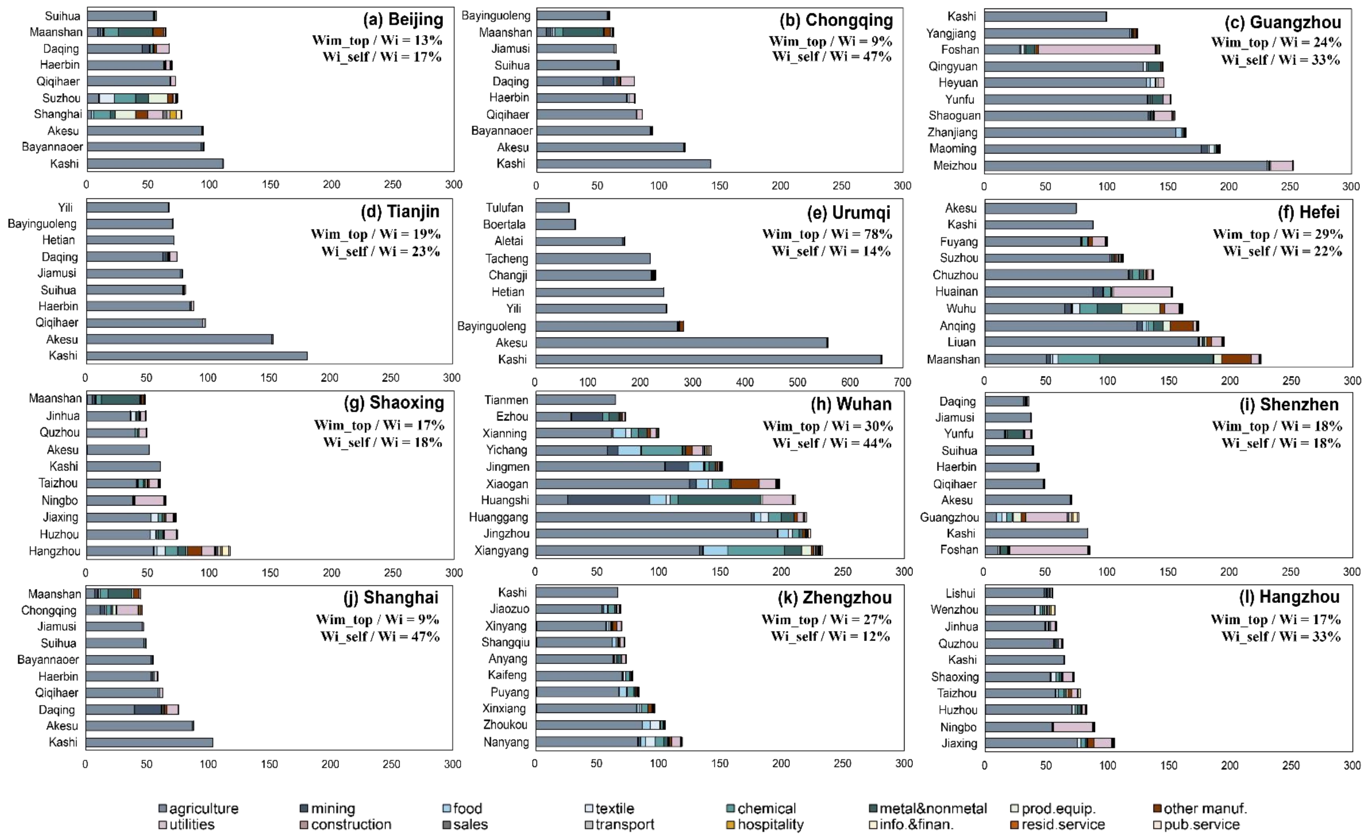

Figure 8- 4: Top 12 water-imported cities (net water import > 2 Bts) and top 10 cities where they had water imported from (except themselves). The unit of the above figure is Mts. Except Urumqi (0-700 Mts), the x-axis in the other cities is ranged from 0-300 Mts. These top water importers are arranged based on the volume of net water import in a descending order (from a to l).; Wim_top/Wi represents the percentage of water imported from top 10 cities in a city's total water inflow; Wi_self/Wi is defined as the percentage of self-supplied water in a city's total water inflow. Abbreviations of economic sectors include prod. equip. (production equipment); other manuf. (other manufacturing); info. & finan. (information & finance); resid. service (residential service); pub. service (public service).

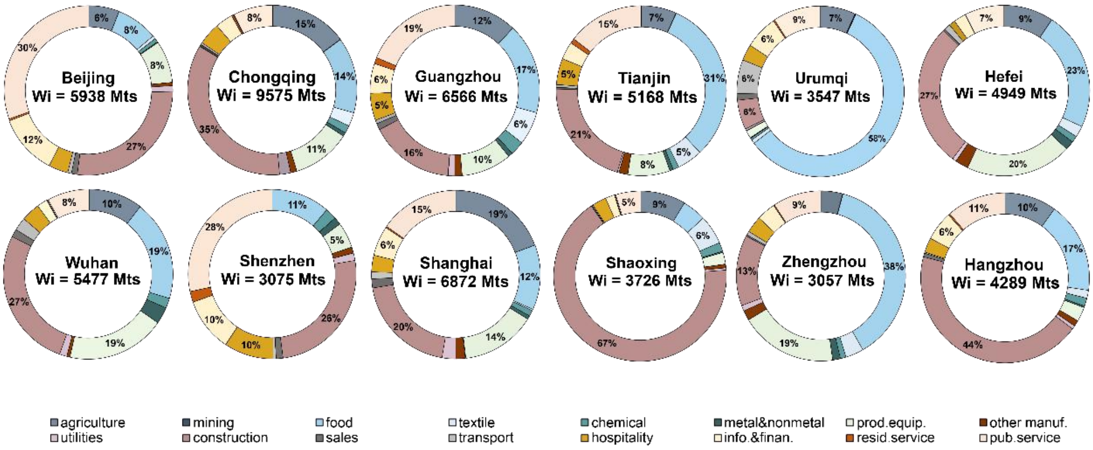

Figure 8- 5: Top 12 water-imported cities and major economic sectors where they consumed their water inflows

Figure 8-4 and Figure 8-5 reveal the water imbalance exists in specific cities or economic sectors with the focus on characteristics and comparison of large water importers. To start with, water dependency unveils the water conflicts of certain cities in the virtual water supply chain. Observed from Figure 8-4, a city could be self-dependent or highly reliant to surroundings. In Urumqi, 78% of virtual water inflow came from its top 10 water exporters, mainly in Xinjiang. These top exporters, however, all experienced serious or severe water stress except Altay, Ili, Bayingol. In contrast, the percentage of self-supplied water was the highest in Chongqing (47%), Wuhan (44%), and Shanghai (47%), but Wuhan and Shanghai were faced with serious and severe water stress themselves. Unlike Chongqing (9%) and Shanghai (9%), approximately 30% of Wuhan's virtual water inflow was derived from its top 10 exporters, among which the criticality ratios in Xiangyang and Ezhou reached 207% and 103% respectively. Furthermore, some larger water importers also heavily relied on the other large water-imported cities, shown in virtual water flows from Shanghai to Beijing, from Chongqing to Shanghai, from Guangzhou to Shenzhen, in-between Hangzhou and Shaoxing, and the contributions of a mix of economic sectors in these cities can be acknowledged.

Second, water inputs and economic gains among cities were not in proportion. According to calculation, Shanghai (139 CNY/tonne), Beijing (134 CNY/tonne), and Shenzhen (109 CNY/tonne) had relatively high economic carrying capacity values for per unit water import. Seen from Figure 8-5, water inflows to info. & finan. in these cities were relatively large, equaling to 412, 713, 308 Mts, taking up 6%, 12%, and 10% of their total water inflows respectively. On the contrary, economic carrying capacity embodied in each unit of water import in Urumqi (17 CNY/tonne) was the lowest among large water importers. Over half (58%; 2057 Mts) of its virtual water was transferred to the food industry.

Third, some pillar sectors were confronted with potential water vulnerability in the virtual water supply chain, reflected in the contradiction of their large volumes of virtual water supply and water stress status. The virtual water in Maanshan was exported to several water importers, such as Shanghai, Beijing, Chongqing, Shaoxing, and Hefei (Maanshan was Hefei's top 1 water exporter), and the main economic sectors in Maanshan that supplied water were chemical, metal & nonmetal, and other manuf. Besides agriculture, Daqing exported water from mining to several water importers, especially Shanghai (22 Mts) and Chongqing (9 Mts), whose water import from Daqing's mining sector was ranked as top three on a national scope. Besides, Foshan's utility sector supplied virtual water to Shenzhen and Guangzhou. Nevertheless, Maanshan (149%), Daqing (291%) and Foshan (107%) had their criticality ratios greatly outweigh 80%.

8.5 Summary: The Necessity to Introduce Economic Instruments to Mitigate Water Imbalance Exacerbated by Economic Trade in China's Cities

There is a lack of understanding of China's city-level water footprint studies, and the existing research only covers a few cities or cities in well-known regions. To fill this research blank, this case study investigates the water flows in the supply chains of China's 313 cities for the very first time. This case study uncovers the imbalance between water stress and virtual water flows exacerbated by the current economic trade, and emphasises the urgency to introduce economic instruments to mitigate the water imbalance:

First, it can be seen geographically that China's seven regions took main responsibilities for water export in different industries, and those regions responsible for agriculture and industry needed more economic instruments to ease their water stress. The current economic trade among China's seven regions determined China's water imbalance in agriculture, industry and service at the national scope (Table 8-3). In terms of agriculture, Northeast and Northwest were regarded as national agricultural bases to supply a large amount of virtual water to local cities (Table 8-2) and to other regions such as East China and South China, which exacerbated their water stress as they were the regions with the most severe water scarcity (Figure 8-1). For industry, East China dominated in industrial virtual water inflows and outflows as China's top 1 comprehensive industrial base (Hu-Ning-Hang or Yangtze River Delta Industrial Zone). Central China also occupied relatively large virtual water flows in the industry. Wuhan, a major city in Central China, had water inflows from more diverse economic sectors compared with the other cities, including both light- (food, textile) and heavy-industrial sectors (such as chemical in Xiangyang, mining and metal&nonmetal in Huangshi) (Figure 8-4 8-4). Regarding service, coastal areas had overwhelming advantages over inland in aspects such as financial markets and public service facilities, represented by China's four megacities, Beijing in North China, Shanghai in East China, Guangzhou and Shenzhen in South China.

Second, major water exporters were inclined to suffer from more severe water stress but obtained less economic gains, and these water exporters required the aid of economic instruments. The relationship between water stress and net water import of China's 313 cities reflected the overall status of water imbalance (Figure 8-3). The number of water exporters outweighed water importers (Table 8-1) which indicated that the water imported by certain cities required rallying support of their surroundings or remoter cities, especially the support of specific cities with large volumes of water export. It was seen that the number of water importers (62%; 85/138) at serious and severe water stress levels occupied a larger percentage than that in water exporters (47%; 83/175) (Table 8-1). Hence, from an overall perspective, water stress was inclined to be a tougher problem for water importers. Meanwhile, it can be seen that China's virtual water flow from cities with high water intensity to low water intensity (Table 8-2), which meant that the water exporters, especially the top water exporters, needed to withdraw more local water to generate per unit output. And it was mainly because that over 95% of total withdrawn by the top water exporters was from the highly water-intensive agricultural sector. This phenomenon greatly impeded the water sustainability for Chinese cities so that economic instruments need to be introduced.

Third, the current economic trade put great stress on three types of cities/economic sectors, and it was necessary that economic instruments were introduced to alleviate water stress in these cities/economic sectors. They were:

(1) cities that were highly self-dependent and/or heavily reliant on other cities' virtual water. These cities were more inclined to confront potential water vulnerability, especially when they and/or their top virtual water exporters were already under water stress. For example, 78% of Urumqi's virtual water inflowed from its top 10 water exporters, and 7 of them were under serious or severe water stress. Wuhan (44%) and Shanghai (47%) had the largest percentages in self-supplied water, but they themselves were confronted with severe water stress. Meanwhile, Wuhan had 30% of virtual water inflowed from its top 10 water exporters, especially from cities with fairly large criticality ratios Xiangyang (207%) and Ezhou (103%). Assuming a water crisis occurred to Urumqi, Wuhan, and Shanghai, they would have been stuck in a dilemma as neither could they restore their water supply, nor could their risks be easily averted by relocating local production activities in other cities and/or sourcing new product suppliers immediately. And some large water importers also depended on each other with virtual water flowing among them, such as from Shanghai to Beijing, from Chongqing to Shanghai, from Guangzhou to Shenzhen. It was likely because these developed cities had strengths in cutting-edge technology and thus produced with higher quality and lower costs, which made them irreplaceable. (2) cities with unequal water investment and economic returns (Figure 8-5). Shanghai's (139 CNY/tonne), Beijing's (134 CNY/tonne), and Shenzhen's (109 CNY/tonne) economic carrying capacity values for per unit water import were large, which was partly due to the prosperity of their financial markets. In contrast, Urumqi, with over half of its virtual water import transferred to low value-added food

manufacturing (58%; 2057 Mts), failed to carry substantial economic gains with per unit water input (17 CNY/tonne). (3) particular economic sectors in certain cities that undertake great responsibilities for virtual water supply even though it was beyond the scope of their capabilities (Figure 8-4). For example, Maanshan had a large amount of virtual water outflows from its economic sectors, especially chemical and metal&nonmetal. This was because Maanshan owned one of the largest iron-ore sites in China, and heavy industry was the pillar to its economy (For its industrial enterprises above designated size, the ratio between GDP in heavy and in light manufacturing was 8:2.). Yet its water withdrawal-to-water availability ratio reached 149%. Daqing transferred its virtual water in mining to several cities, especially Shanghai as Shanghai's land formation was later than other cities, which gave rise to its want of mineral resources. However, its water withdrawal was almost triple the water availability.

Chapter 9 National Water Management through the Transformation of Economy and Development Patterns

9.1 Introduction

China has been undergoing profound transitions over the past decade. Its rapid urbanisation since the 1980s has been labelled as 'China's growth miracle' with approximately 1.06% of annual urban population growth from 1980-2019 (19.39-60.60%), which has dramatically stimulated China's economy (Wu, 2003; NBS, 1980-2020). In 2014, China had stepped into the 'new normal' phase, and achieved optimisation of economic structures (Mi et al., 2017). It means that China's development was no longer driven by investment but innovation and environmentally friendly technology, and the transitions have been accomplished from high-speed to medium-high-speed growth, and from rapid growth of scale to intensive- and quality-increasing growth (CSC, 2021b; C. Zhang et al., 2019). Additionally, as the world's largest exporter, China also has its economy driven by international trade. Since the 2008 global financial crisis, its traditional international markets have transformed in order to tackle increasing trade barriers against China (Viju & Kerr, 2012). Confronting with more south-south trade in the new phase of globalisation, China has also relocated a part of its production activities to other developing countries (Meng et al., 2018). Hence, it is necessary to investigate the dynamics of China's water quantity and water quality triggered by these transitions. This chapter quantifies China's direct and embodied water use and COD discharge from 2010-2015 and in turn explores how national water could be managed through the transformation of economy and development patterns. Economic sectors covered in this research can be found in Table A9. The work in this chapter has been published in Environmental Research Letters (Li, Shan, et al., 2019).

9.2 Identify Key Producer and Consumer Sectors in the Virtual Water Supply Chain

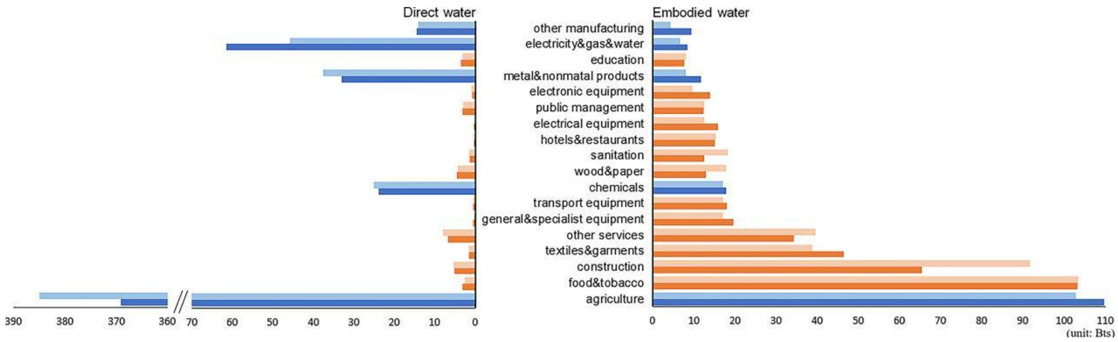

Figure 9-1: Direct and embodied water use across sectors in primary, secondary and tertiary industries in 2010 and 2015. Blue and orange bars represent producer and consumer sectors respectively. Bars with dark blue/orange and light blue/orange indicate water use data in 2010 and 2015 respectively.

In the virtual water supply chain, producer sectors represent water suppliers that transfer water to other sectors via trade, with their direct water use outweighing their embodied water use. On the contrary, consumer sectors are water consumers that consume water transferred from other sectors via trade, and these sectors occupy more embodied water use than direct water use. Figure 9-1 compares direct and embodied water use across sectors in primary, secondary and tertiary industries in 2010 and 2015, and identifies major producer and consumer sectors in the virtual water supply chain. Agriculture was the most significant producer sector. Its direct water use accounted for approximately 70% (369 Bts/534 Bts in 2010 and 385/540 Bts in 2015) of China’s total amounts, but embodied water use in this sector only took up about 20% (110/534 Bts in 2010 and 103/540 Bts in 2015) of the total, which underlined the irreplaceable role that agriculture played as a dominant producer sector in the virtual water supply chain. Electricity&gas&water was the second-largest producer sector (especially electricity), followed by metal&nonmetal products (metallurgy in particular), chemicals and other manufacturing. Conversely, food&tobacco and construction were dominant consumer sectors, followed by textiles&garments and other services. In addition, all sectors in the tertiary industry were water consumers. From 2010-2015, gaps in direct and embodied water use had experienced changes in several sectors. As for producer sectors, agriculture’s direct water use increased by 16 Bts while its embodied water use declined by 7 Bts. Direct (33-38 Bts) and embodied (12-8 Bts) water use in metal&nonmetal products also showed similar patterns. In contrast, direct water use in electricity&gas&water experienced a sharp reduction (62-46 Bts) with its embodied water use fluctuating around 7-8 Bts. Regarding consumer sectors, construction’s embodied water use soared (65-92 Bts) while its direct water use remained at around 5 Bts. Similar patterns were also seen in wood&paper, sanitation and other services.

Agriculture and electricity were the most important producer sectors in the virtual water supply chain. Despite agricultural product types and energy types (including renewable energy), irrigation water use and cooling water use were required. And direct water used in agricultural products (including agricultural by-products) and in electricity generation then benefited other production processes and human settlements. Heavy manufacturing also included vital producer sectors in the virtual water supply chain because water-intensive final or semi- products in these sectors were often redistributed to other production lines as raw materials. The above messages can at the same time explain why large-scale sectors, such as food&tobacco, construction, textile&garments occupied the largest embodied water use. It is worth mentioning that Chuai et al. (2015) found that materials used in construction triggered a large amount of embodied CO_2 emissions. In this case study, we further validated that these materials in construction also embodied a large amount of water use. However, changing patterns of water use in these sectors differed from 2010-2015: 1) agriculture supplied more water to other sectors; 2) electricity transferred less water to other sectors; 3) construction consumed more water from other sectors. The increase of direct and embodied water use in agriculture and construction indicated the growing demand, which can be reflected in the skyrocketing value-added GDP in these sectors from China statistic yearbooks (NBS, 2010-2015). Regarding electricity, the reduction of direct water use in the sector was attributed to higher water efficiency. According to China statistic yearbooks (NBS, 2010-2015), from 2010-2015, the percentage of China's coal consumption for electricity generation declined from 76.2%-72.2%, while natural gas and renewable energy consumed to generate electricity grew from 4.1% to 4.8%, and from 10.4%-14.5% respectively. As more coal is required than other energy types in order to generate the same amount of electricity, direct water use in electricity would inevitably decrease with more efficient water distribution.

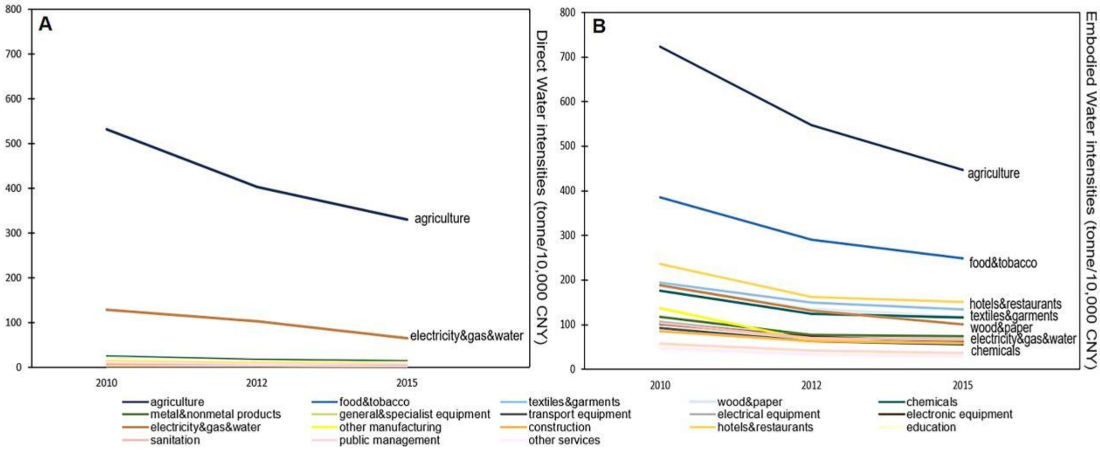

Figure 9- 2: Direct and embodied water intensities across primary, secondary and tertiary industries in 2010, 2012 and 2015. (9-2A) direct water intensities. (9-2B) embodied water intensities.

Figure 9-2 depicts the comparison between direct and embodied water intensities. Overall, embodied water intensities outweighed direct water intensities, and both direct and embodied water intensities presented downward trends from 2010-2015. Agriculture occupied the largest direct and embodied water intensities, and the reduction of its intensities was the sharpest, by approximately 40%. It was previously shown that its direct water use was three times the amounts of its embodied water, but its embodied water intensities (724-447 tonne/10,000 CNY) was larger than its direct water intensities (533-330 tonne/10,000 CNY). Electricity&gas&water was ranked as the producer sector with the second-largest direct water intensities (129-66 tonne/10,000 CNY), but its embodied water intensities were still larger (188-100 tonne/10,000 CNY). On the contrary, food&tobacco had the second-largest embodied water intensities (386-248 tonne/10,000 CNY), but the ranking for its direct water intensities was much lower. Construction and textiles&garments also had far larger embodied water intensities than their direct water intensities. Yet embodied water intensities in construction were smaller than those in textiles&garments even though embodied water use in construction was larger.

It can be observed that embodied water intensities tended to surpass direct water intensities in major producer sectors in the virtual water supply chain even though direct water use outweighed embodied water use in these sectors. This illustrates our previous point that major producer sectors, especially agriculture and electricity, contributed large water inputs to generate large production outputs. In contrast, major consumer sectors had both larger embodied water use and embodied water intensities than their direct water use and direct water intensities. It meant that the large amounts of embodied water use in these sectors were not only affected by their huge consumption but also large embodied water intensities. In construction, its embodied water use soared (Figure 9-1) while its embodied water intensities decreased from 2010-2015, which signified the rapid development of China's infrastructure construction and real estate, and the role it played as a solid measure to jumpstart the economy and spur employment, especially in the post-financial crisis era (Giang & Sui Pheng, 2011).

9.3 Economy and Development Patterns Benefit China's Overall Embodied Water

From 2010 to 2015, China's total embodied water use fluctuated within a reasonable range from 2010 (534 Bts), 2012 (548 Bts) to 2015 (540 Bts), and its embodied COD discharge dropped gradually during the period (17.74-15.29 Mts). Yet embodied water intensities (113-67 tonne/10,000 CNY) and embodied COD intensities (38-19 tonne/10-8 CNY) both declined tremendously during the period.

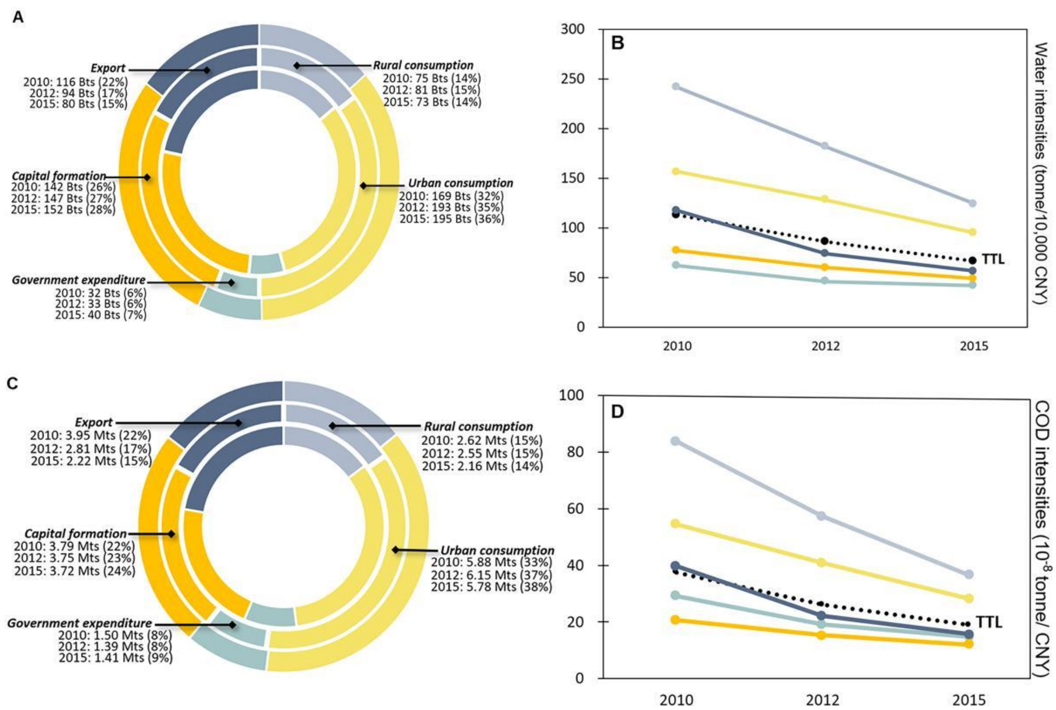

Figure 9- 3: Embodied water use and COD discharge, and their embodied intensities categorised by final demands. (9-3A) and (9-3C) depict embodied water used and COD discharged in each final demand respectively, where the concentric circles from interior to exterior represent 2010, 2012 and 2015 respectively. (9-3B) and (9-4D) illustrate embodied water and COD intensities in final demands, indicating embodied water use and COD discharge per consumption by each final demand. The dotted black line (TTL) represents total embodied water or COD intensities, calculated as total embodied water use or COD discharge divided by total consumption. Colours highlight the final demands remain the same in four graphs.

Figure 9-3 demonstrates embodied water use and COD discharge contributed by different final demands. Among all the final demands, urban consumption had the largest amounts of embodied water use (169-195 Bts) and embodied COD discharge

(5.88-5.78 Mts), followed by capital formation, while government expenditure was the smallest embodied water user (32-40 Bts) and embodied COD discharger (1.50-1.41 Mts). And the dynamics showed that the percentages of water use and COD discharge embodied in export declined dramatically (by 7%) while the percentages in urban consumption grew fast (by 4%-5%). However, government expenditure contributed more for embodied COD discharge (8%-9%) than for embodied water use (6%-7%). Conversely, capital formation held larger percentages in embodied water use (26%-28%) than in embodied COD discharge (22%-24%). Moreover, embodied water and COD intensities in final demands all reduced. Compared with previous research conducted from 1992-2010 (Guan et al., 2014), the overall reduction rates of embodied water and COD intensities tended to be steadier. From 2010-2015, the reduction of embodied water and COD intensities during 2012-2015 furthermore slowed compared with 2010-2012, especially in export (117-57 tonnes/10,000 CNY). The dotted black lines (TTLs) represent total embodied water and COD intensities. Embodied water and COD intensities in certain final demand that were higher/lower than these bars indicated that this final demand required and generated more/less embodied water use and COD discharge to meet per unit of consumption than average national levels. It was clear that only urban and rural consumption sat above the dotted black lines (TTLs), but embodied water and COD intensities were much larger in rural consumption than in urban consumption. Below the TTLs were export, capital formation and government expenditures. Export had the third-largest embodied water and COD intensities, and government expenditures and capital formation ranked last in embodied water and COD intensities respectively.

The overall changing patterns of embodied water use and COD discharge, and embodied water and COD intensities marked the advancement of water-saving and water pollution control in China. The slower reduction of embodied water and COD intensities from 1992-2015 was attributed by long-term water management and recent years' economic slowdown (C. Zhang et al., 2020). In the future, technology breakthroughs would be the most effective approach to obtaining a faster reduction of embodied water and COD intensities. From demand perspectives, large amounts of water use and COD discharge embodied in urban consumption and capital formation formed the prerequisite for advancing urbanisation at an unprecedented rate. Given that less water use and COD discharge were required and generated to meet per unit of consumption in urban areas than in rural areas, it can be inferred that urban areas can better manage water use and control water contamination than rural areas, which supported the point of view raised by the previous researcher that urbanisation to some extent alleviates China's water issues (Wu et al., 2012). China's plummeted embodied water use (116-80Bts) and embodied COD discharge in export (3.95-2.22 Mts), and doubled export values (11-25 trillion CNY) from China statistic yearbooks (NBS, 2010-2015) implied that more high-value-added products than water-intensive low value-added products were preferred for export during the study period.

9.4 Water Structure Optimisation by Domestic and International Industrial Upgrade

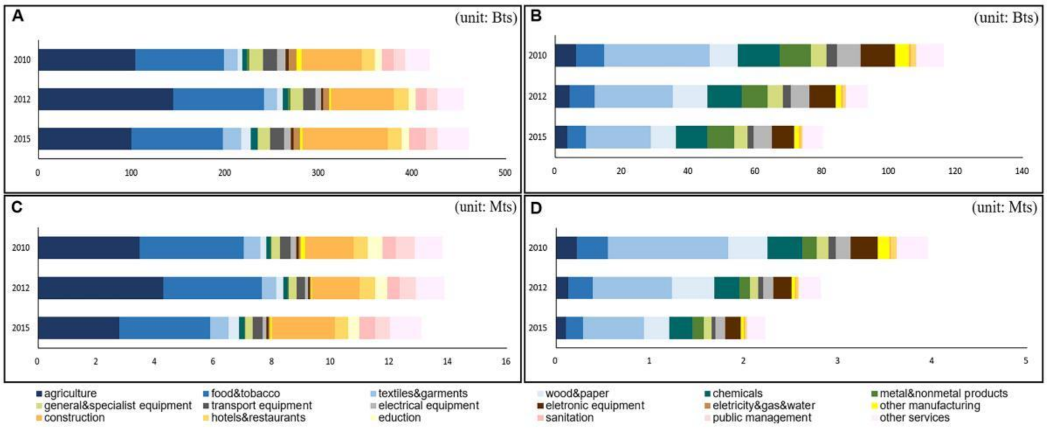

Figure 9- 4: Embodied water use and COD discharge across sectors in domestic consumption and in export. (9-4A) embodied domestic water used for domestic consumption. (9-4B) water use embodied in export. (9-4C) embodied domestic COD discharged for domestic consumption. (9-4D) COD discharge embodied in export.

Figure 9-4 presents embodied water use and COD discharge across sectors in domestic consumption (including rural and urban consumption, government expenditures and capital formation) and in export in 2010, 2012 and 2015. Regarding domestic consumption, agriculture, food&tobacco and construction were the largest embodied water users and COD dischargers. Agriculture experienced ups and downs in both embodied water use (103-99 Bts) and embodied COD discharge (3.46-2.77 Bts). And embodied water use (by 26 Bts) and embodied COD discharge (by 0.51 Mts) in construction surged. Besides these sectors, textiles&garments, sanitation, transport equipment, hotels&restaurants, public management, wood&paper also had large amounts of both embodied water use and COD discharge. However, general&specialist equipment was a large embodied water user but not a large embodied COD discharger, while education discharged large amounts of embodied COD but its embodied water use was relatively small. From 2010-2015, embodied water use in light-manufacturing sectors for domestic consumption presented an upward trend. On the contrary, embodied water use in heavy-manufacturing sectors declined (except chemicals and transport equipment), where the embodied water use in metal&non-metal products dropped at the fastest speed (by 2 Bts), followed by general&specialist equipment, electrical equipment and electricity&gas&water. Besides, embodied water use in each tertiary sector rose during the period, especially sanitation (by 6 Bts) and hotels&restaurants. Similarly, embodied COD discharge in heavy-manufacturing sectors reduced (except chemicals), with the greatest decrease in electrical equipment (by 0.06 Mts).

With regard to export, it was apparent that textiles&garments occupied a predominant role in both embodied water use (31-19 Bts) and embodied COD discharge (1.28-0.65 Mts). The embodied water use and COD discharge were also both large in chemicals, electronic equipment, food&tobacco and wood&paper. Yet for metal&nonmetal products, its embodied water use was ranked as the top, but its embodied COD discharge had a smaller ranking. Furthermore, the largest embodied water users and COD dischargers in domestic consumption included sectors across primary, secondary and tertiary industries, while only primary and secondary sectors were listed as the largest embodied water users and COD dischargers in export. During 2010-2015, both embodied water use and COD discharge for export fell in each sector. The reduction of embodied water uses (32-19 Bts) and embodied COD discharge (1.28-0.65 Mts) in textiles&garments was the sharpest. In the textile sector, both water use (21-9 Bts) and COD discharge (0.86-0.30 Mts) embodied in exported products plummeted even though its embodied water use (1-3 Bts) and embodied COD discharge (0.05-0.11 Mts) for domestic consumption increased.

China's domestic water structure optimisation was manifested in the fact that embodied water use in heavy-manufacturing sectors (except chemicals and transport equipment) dropped while that in light-manufacturing and tertiary sectors increased, and embodied COD discharge decreased in heavy-manufacturing sectors (except chemicals). It demonstrated the improving water status under industrial transformation and upgrade within the country. From international perspective, textile was the largest water exporter. However, it can be found from China's input-output table that the total outputs for textile's domestic consumption (68-212 billion CNY) increased while the same indicator for its export (873-607 billion CNY) dropped. Combined with the water quantity and quality data in textile, it revealed that China's textile products, along with water use and COD discharge embodied in these products, were partly transferred from international markets to domestic markets in the post-financial crisis era and the new phase of globalisation, when more trade barriers had been set and some of its production activities had been relocated in other developing countries to save the cost of labour and materials (Meng et al., 2018; Viju & Kerr, 2012). Yet China's dominant water exporters were still primary and secondary sectors.

9.5 Summary: The Transformation of Economy and Development Patterns as Catalysts for Effective National Water Management in China

Among the existing water footprint studies, research associated with water quantity or water scarcity outweighs those related to water quality or water pollution, and these studies seldom observe China's water footprint under policy backgrounds. Bridging this research blank, this case study analyses the influences of economy and development policies in the past decades on its latest available embodied water quantity and water quality. This case study quantifies the dynamics of China's embodied water quantity and quality across individual economic sectors from 2010-2015, and thus the alleviation of China's water scarcity and pollution under specific domestic (urbanisation, 'new normal' phase) and international (post-financial crisis era, new phase of globalisation) context can be seen. In turn, this analysis suggests feasible solutions to effective national water management through the transformation of economy and development patterns:

First, domestic energy policy and economic stimulus directed the optimised water use and the reduced water pollution in key producer and consumer sectors in the virtual water supply chains, electricity and construction. Agriculture and electricity were the most significant producer sectors that supplied virtual water to other production sectors (such as food manufacturing) and human settlements, but direct water in agriculture increased by 16 Bts (369-385 Bts) while that in electricity declined. This was because that electricity was greatly impacted by the transition of China's energy structure, from taking coal as a leading resource to energy diversification, especially renewable energy. As an important consumer sector, construction had its embodied water use and COD discharge skyrocket (65-92 Bts) during 2010-2015 as developing infrastructure construction and real estate enabled a boost to the national economy, especially in the post-financial crisis era (Giang & Sui Pheng, 2011). However, agriculture and construction could further reconsider their growth patterns, such as further improving water-drip irrigation technology and applying more environmentally friendly construction materials (Fan et al., 2020; González & García Navarro, 2006).

Second, urbanisation alleviated the water crisis to some extent, and China had the resolution to encourage urbanisation without sacrificing the aquatic environment (Wu et al., 2012). Embodied water and COD intensities were much lower in urban consumption than in rural consumption, which proved that urban areas had the ability to better manage water use and control water pollution than rural areas. It was also seen that the embodied water use and embodied COD discharge in urban consumption accounted for a larger percentage of China's total embodied water use and embodied COD discharge from 2010-2015. Yet China is currently in the second stage of urbanisation while developed countries have entered the third stage, so there is still a long way to go (Northam, 1979; Wang et al., 2019).

Third, the optimisation of economic structures and fulfilment of industrial transformation and upgrade in domestic markets fundamentally altered China's local water distribution. The 'new normal' phase brought substantial achievements in water-saving and water pollution control. From 2010-2015, embodied water and COD intensities in all final demands presented downward trends, and the reduction rates of embodied water and COD intensities from 2012-2015 were lower than those during 2010-2012, which was partly attributed to the transition from high- to medium-high growth speed of the country (C. Zhang et al., 2020). Besides, the overall trend showed that embodied water use in light-manufacturing and tertiary sectors grew, while embodied water use in heavy-manufacturing sectors (except chemicals and transport equipment) reduced dramatically (especially in metal&nonmetal products), and embodied COD discharge in heavy-manufacturing sectors (except chemicals) also reduced (especially in electrical equipment).

Fourth, the changes in the international situation also gave impetus to China's optimised water allocation. In the post-financial crisis era, China has grasped the opportunity to adjust water use patterns while maintaining the export market's vitality. From 2010-2015, embodied water use (116-80 Bts) and COD discharge (3.95-2.22 Mts) in export plummeted, but China's export values still soared (11-25 trillion CNY), especially in textile&garments. It was because China had focused more on high value-added over low value-added markets since the global financial crisis in order to sharpen its competitive edges under the influence of trade barriers. In addition, some comparatively low-end sectors, such as textiles, tended to shift their embodied water use and COD discharge from international to domestic markets instead when some production activities had been transferred to other developing countries in the new phase of globalisation to pursue cheaper labour market and materials, which marked the rise of South-South trade (Meng et al., 2018).

Chapter 10 Discussion

Considering that this thesis includes four individual case studies that cover different research topics, research areas and even research scopes, this chapter aims to bring these empirical results together and discusses the main findings, especially commons they have. This section aims to talk about two overarching questions in this thesis: negative or positive effects brought by economy and development patterns on water scarcity and water pollution, and then potential approaches for the mitigation of water scarcity and water pollution through the adjustment of economy and development patterns.

10.1 Negative or Positive Effects on Water Scarcity and Water Pollution Brought by Economy and Development Patterns

This section aims to discuss effects (both negative and positive) brought by economy and development patterns on water scarcity and water pollution based on four empirical studies. Regarding negative effects (empirical results from Chapter 6 and Chapter 8), they include:

- Economic disparities and development gaps among regions, or among cities in a specific region, normally enlarge over time without intervention, and water inequality would grow. And the exaggerated water inequality would then further deteriorate the overall water status and issues such as undermined water balance and spreading water contamination would raise due to the flowing nature of water resources. In China, this phenomenon can be more often seen among cities in a region as each region is likely to have one or a few economically prosperous cities. And these well-developed cities normally have large population (correspondingly large volume of water withdrawal/use/consumption), but they tend to have high water efficiency due to technological development. However, these cities often heavily rely on product import and virtual water inflows from external cities that are agriculture- or manufacturing-oriented. This will further deprive water resources or deepen water pollution in less-development cities. Taking Beijing and Tianjin as an example, it can be seen from Chapter 6 and Chapter 8, Beijing and Tianjin have the densest population (Figure 6-1) but they have large amounts of net water import (Figure 8-2). But their surrounding or even remoter cities normally take a great burden as net water exporters to meet their demands, such as Beijing's and Tianjin's manufacturing sectors, and Tianjin's food sector (Figure 8-5). However, Beijing's and Tianjin's water efficiency are normally far lower than other cities (Figure 6-3).

  A more specific example is manifested in the 2012 water utilisation of energy sectors in the BTH (Chapter 6). Beijing and Tianjin had the largest population, at 21 million people and 14 million people and generated the largest total output of energy sectors, at 550 billion CNY and 452 billion CNY (Figure 6-1). Even though Beijing and Tianjin had the largest direct water withdrawals (203 Mts and 108 Mts) (Figure 6-2), but their water intensities were the lowest (4×10^{-4} tonne/CNY and 3×10^{-4} tonne/CNY) (Figure 6-2), which meant their water efficiency in energy production was rather high due to their prosperous economy and sound development. Their embodied water withdrawals (6690 Mts and 1328 Mts) (Figure 6-2), however, far exceeded most of the cities in the BTH. This implied that Beijing and Tianjin might outsource many water-intensive products or raw materials from other places to meet their demands. By contrast, although in the same region, Baoding's water intensity was the lowest, at 19×10^{-4} tonne/CNY (Figure 6-2), and Chengde only had 17 Mts' direct water withdrawal but its water intensity reached 8×10^{-4} tonne/CNY (Figure 6-3).

- Unsuccessful division of labour among regions/cities, or unoptimised industrial structure in a region/city could easily lead to the low water efficiency, especially in water-intensive industries/economic sectors. Due to resources abundance, each region or city has their own advantageous industries or economic sectors. If a region or city does not focus on what they already have strengthens in the supply chain but have a blind expansion on the scale of economic activities, it is likely that the region or city would not be able to pay good attention to both superior and inferior industries or economic sectors, and dispersed water resources allocation in different segments of its supply chain would then reduce its overall water efficiency.

  China has several regions that take main responsibilities for different types of economic production, which could be categorised as agriculture (Northeast China and Northwest China), industry (East China), service (coastal regions) (Table 8-3). And each region also forms its own economic circle with various economic activities, with cities having prominent advantages in a variety of industries or economic sectors. However, regions might have different types of agricultural supply due to factors such as geographical convenience or eating habits. Assuming that these characteristics are not taken into consideration, chaotic allocation of economic activities would hinder water efficiency and the lack of production scale would impede the water optimisation. Similarly, a city also has its own unique economic structure. A city needs to proportionally distribute the ratios of their industries or economic sectors according to their resources endowment and industrial foundations accumulated over a long period of time. In each industry or economic sector, production activities could also be categorised into activities during preparation stages (the production of raw materials or equipment) and activities directly target for final product outputs. If a city is involved with multiple production activities, which are even not in the same category, water efficiency would be lowered as water resources could have been centralised for more specific or more similar production operations.

The case study in Chapter 6 also illustrates this point by analysing the 2012 water structures in energy sectors in the BTH' cities. It was seen that every single city in the had water withdrawals in electricity production, the energy sector accounted for 69% (669 Mts/965 Mts) of the total direct water withdrawal in the BTH region, even though some cities had rather low water intensities in this sector, such as Zhangjiakou (13 x 10^{-4} tonne/CNY), Langfang and Hengshui (14 x 10^{-4} tonne/CNY). This showed that the region did not construct a complete energy supply chain that had each city only contribute to manufacturing of specific components or assembling processes for an electricity generator, or standardised machinery in electricity. In the meantime, the BTH region's energy production activities could be categorised into two types: energy resources excavation (coal, extraction) and energy processing (coking, electricity, gas). Compared with Cangzhou who showed water advantages in one type of energy production activity (coal, extraction), the water efficiency appeared obviously lower in Shijiazhuang and Xingtai who managed two types of energy production activities simultaneously (coal and cooking) (Figure 6-2).

- Economic trade without much consideration of virtual water embodied in supply chains is likely to cause several regions or cities' mismatch between water stress and virtual water supply, which would be worse when virtual water supply does not equal to economic gains. The nature of virtual water determines that China sometimes neglects the urgency to improve water status of regions or cities with great responsibilities to export products with large amounts of embodied water but also with water stress themselves. And this neglect would prevent the country from the overall water sustainability. According to empirical results in Chapter 8, it is obvious that China's current economic trade has aggravated its water imbalance. In China, many regions or cities dominated by water-intensive industries or economic sectors, mostly agriculture- and manufacturing-oriented regions (such as Urumqi's agriculture, Maanshan's chemical and metal&nonmetal, Daqing's mining), are still bearing great water stress just to meet the demands of a few regions or cities with large population (such as Beijing's public service, Zhengzhou's food) (Figure 8-5). However, the regions or cities being supplied with large amounts of virtual water often have huger potentials to generate economic revenues than those virtual water suppliers because their orientations are on highly value-added service-related industries or economic sectors.

  Under this economic trade situation, however, another type of cities' water status could also be negatively affected, depending on their water dependency. Some of these regions or cities (such as Urumqi) heavily rely on other regions' or cities' virtual water supply, even some water-stressed regions or cities (Figure 8-4). Considering the unpredictability of water availability (related to several natural factors such as rainfall, iceberg melting), these regions or cities with dependency would not only confront with shortfall in supplies but also need to temporarily alter their water structure to at least satisfy the basic needs of its residences by investing in water-intensive products when water shortage occurs to regions or cities that they source products from. This will greatly affect these regions or cities' water resilience in the later stages. On the contrary, some of the cities are self-reliant to a great extent (such as Wuhan and Shanghai) (Figure 8-4). Similarly, single source will inevitably lead to water vulnerability when local Water calamities happen.

Chapter 8 examines the 2015 water footprint embodied in economic trade among China's 313 cities and found an imbalanced relationship between water stress and virtual water flows. China's top 10 water exporters experienced severe water stress, having their water withdrawal-water availability ratios over 340% (Figure 8-1 and Figure 8-3), far higher than China's top 10 water importers, at around 200% (Figure 8-3). What is worse, China's virtual water inclined to flow from cities with high water intensities to those with low water intensities (Table 8-2), which meant that water exporters withdrew more local water resources but generated less economic outputs. This case study is a typical example stating the consequences of not considering virtual water embodied in supply chains in economic trade.

Regarding positive effects (empirical results from Chapter 7 and Chapter 9), they include:

- The optimisation of economic structure and the fulfilment of industrial transformation could catalyse the improvement of water management to a large extent, including the reduction of water withdrawal/consumption and the control of water pollution. Economic structure adjustment or industrial transformation normally accord with the relatively mature stage of economic growth as well as a great leap of technological advancement. This could be seen in two specific examples in this thesis.

  Chapter 9 quantified the dynamics of China's embodied water use and COD discharge at the national level from 2010-2015. During the study period, China' embodied water use (523-540 Bts) remained stable and its embodied COD discharge (17.74-15.29 Mts) reduced. Yet its embodied water intensities (113-67 tonne/10,000 CNY) and embodied COD intensities (38-19 tonne/10,000 CNY) all dropped dramatically (Figure 9-3). Besides the development of technology, China also underwent an economic structure upgrade, from high-to medium-high speeded economic growth, and from water-intensive/water-polluted low value-added industries/economic sectors to water-conserved high value-added industries/economic sectors (C. Zhang et al., 2020). It was observed that China curbed the expansion on heavy manufacturing and encouraged the development of light-manufacturing and tertiary industry (Figure 9-4).

Chapter 7 accounted the anthropogenic NH_4^+ discharge of all the cities in the PRB from 2011 to 2017. The PRB had the largest reduction of NH_4^+ discharge in agriculture (66.55-36.35 Kts, declined by 45%) (Table 9-1), especially in the cities with the sharpest decreases in agricultural NH_4^+ intensities such as Ganzhou, Zhaoqing and Qingyuan. And these changes were associated with the shrinking of agricultural product demand and the advancement of agricultural technology. The PRB also had reduced NH_4^+ discharge (26.84-15.87 Kts, declined by 41%) in industry, especially in the cities with decreased industrial NH_4^+ intensities, such as Ganzhou's nonferrous melting and Zhongshan's textile, where industrial transformation can be clearly seen in Figure 7-4.

- Economic and social development also contributes to the alleviation of water scarcity and water pollution. First, economic and social development could be associated with both international and domestic situation and corresponding policy. From the international perspective, globalisation brings not only challenges and competition but also brings opportunities for growth and development. Domestically, a country's policy could directly exert influences on its economy and development patterns.

  The case study in Chapter 9 is a great example for this argument. The study period (2010-2015) was post-financial crisis era and there were increasing trade barriers against China (Viju & Kerr, 2012). With the rise of South-South trade, a part of China's production activities, especially those for low value-added products, had also been transferred to other development countries with cheaper labour and material costs (Meng et al., 2018). These international changes encouraged the transformation of China's traditional international market in order to strengthen its competitive edge. China's embodied water use (116-80 Bts) and COD discharged (3.95-2.22 Mts) (Figure 9-3) reduced but its export values (11-25 trillion CNY) still soared. For textile&garments, this sector even shifted its orientation from international to domestic market, with water use (21-9 Bts) and COD discharge (0.86-0.30 Mts) embodied in export declined but embodied water use (1-3 Bts) and COD discharge (0.05-0.11 Mts) for domestic consumption increased.

  During 2010-2015, China also entered the 'new normal' phase for the optimisation of its economic structure (described in the previous point). In addition, China was in the second stage of urbanisation (Northam, 1979). The urbanisation allowed more urban areas to control water overuse and water pollution in a more efficient way (Wu et al., 2012). It was seen that embodied water and COD intensities were much lower in urban consumption than those in rural consumption (Figure 9-3). At that time, China also had energy transitions by replacing a part of predominant traditional energy (coal) with more diverse energy sources (clean/renewable energy). This measure attributed to the reduction of both direct and embodied water use in its electricity (Figure 9-1).

Second, when China's regional planning becomes sophisticated gradually, a region would normally have a well-developed economic circle that accommodates large population and incubates industry leaders with outstanding abilities to deal with water scarcity and water pollution. For example, the case study in Chapter 7 shows that the PRD only had 8 cities but it accounted for almost half of the PRB's total reduction of NH_4^+ discharge (43.69 Kts/134.38 Kts) (Table 7-2).

Third, economic and social development is also related to other aspects, such as residents' environmental awareness. Residents' positive environmental attitude would directly affect their pro-environmental behaviours and weaken negative environmental impacts in household. Nevertheless, residents in well-developed cities have cultivated environmental attitudes and would be more reluctant to further lower their water use standards due to higher incomes and the pursuit of better life quality. In Chapter 7, all the cities, except Guangzhou, had their population grow but their NH_4^+ discharge in household decline. However, the per capita NH_4^+ discharge (6.74×10^{-4} tonne/person in 2011 and 7.63×10^{-4} tonne/person in 2017) of household in Guangzhou was already low.

By summarising all the points of view in this Section, the influences on water scarcity and water pollution could be associated with three economy and development aspects: regional development, economic trade and social development.

10.2 Potential Approaches to Mitigating Water Scarcity and Water Pollution by Adjusting Economy and Development Patterns

Considering the effects on water scarcity and water pollution exerted by economy and development patterns, this section then accordingly suggests potential approaches to mitigating water scarcity and water pollution through the adjustment of economy and development patterns. All potential approaches could be seen in the following figure, linking with the summary of previous influences and with relevant policy recommendations that will be mentioned in Chapter 11.

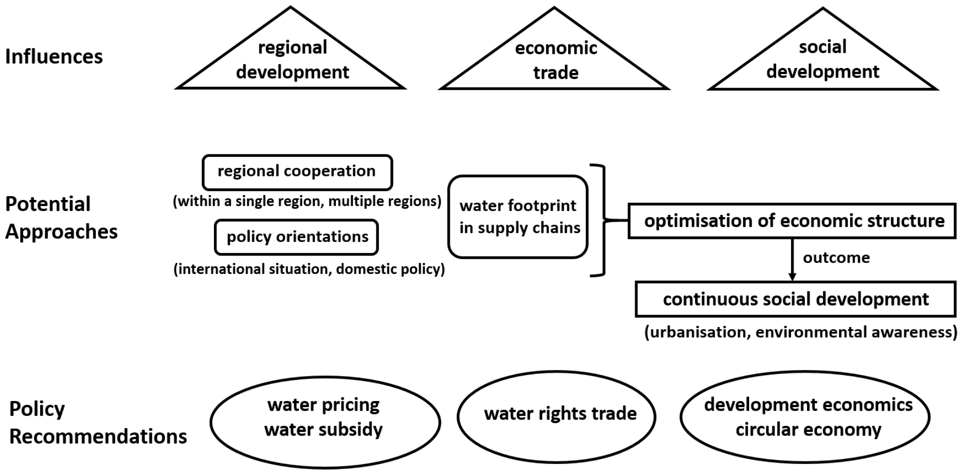

Figure 10-1: Influences of economy and development patterns on water scarcity and water pollution, corresponding potential approaches, and policy recommendations.

It can be seen in the figure that the adjustment of economic structure and continuous social development are two pillars that curb water waste/pollution and facilitate China's water sustainability. To start with, the optimisation of economic structure is inseparable from macroeconomic regulations, and the macro-economy is often influenced by international situation and domestic policy orientations. China should grasp the opportunity to upgrade its economic structure when there are significant changes in international situation. Accordingly, China could also release domestic policy about economic structure transformation and shift its focus from high-speed economic growth to high-quality and water sustainable economic mode. As shown in Chapter 9, China catered to the international environment and responded quickly to the trade/currency war blown after the 2008 financial crisis. The successful transformation of international market (by exporting more water-environmental-friendly and high value-added products) not only increased its export value but also optimised its water structure for exported products. China also took initiatives to update its economic structure when the globalisation and the rise of South-South trade provided a great opportunity to outsource a part of its water- and labour-extensive industries or economic sectors to other less-developed countries. In the meantime, China also released the policy of 'new normal' and simultaneously upgraded its domestic economic structure.

There is also a more proactive approach for China to optimising its economic structure, which is coordinating regional economy/promoting synergistic development and stirring up regions'/cities' enthusiasm for cooperation and mutual growth. Geographically, the economic structure adjustment needs to be starting from a single region. Each region and its cities should clearly define and consolidate their unique advantages in specific industries or economic sectors by forming production scale with improved water efficiency and eliminating industries or economic sectors in cities that require great large water inputs but lack resource endowment and industrial foundations. After the division of responsibilities among regions and cities are clearly defined, regions and cities with similar economic structures should reinforce cooperation. Well-development regions and cities could impart knowledge/experience to less development regions and cities about water-saving technologies and productivity boots. Once the economic circle is formed in the region (an area with reasonable economic distribution and close regional cooperation), the driving effect of the economic circle to its surrounding areas would be achieved. The establishment of an economic circle could often bring development opportunities and advanced water-saving concepts to its surrounding areas as the results of economic and social radiation. According to the case study in Chapter 6, it is necessary for the BTH region to promote synergistic development by three approaches: (1) establishing an energy supply and having cities responsible for different semi-products in one energy economic sector in order to form production scale and to achieve machinery/water-withdrawal standardisation; (2) taping the potentials of each city's energy advantages and adjusting their energy structures; (3) having well-developed cities to offer advice about water efficiency improvement to less-developed cities with similar structures, such as the advice from Tangshan to Handan in coal. And Chapter 7's case study emphasises the significance of optimising the economic/water structure of the economic circle (PRD) to the overall reduction of anthropogenic water pollutants in the PRB.

When all the regions enter a mature development stage, China's overall economic landscape could be relatively comprehensive and its economic structure would become more stable with each individual supply chains clearly identified. In this stage, the consideration of virtual water footprint cannot be neglected as embodied water use directly influences China's water sustainability via economic trade. However, the management of water footprint is intricate and involves the introduction of water trade market, an economic instrument mentioned in Section 11.3. Nevertheless, it is clear that water importers with few sources of products embodied large amounts of virtual water should build a resilience/risk avoidance mechanism to defeat water vulnerability, such as altering trade patterns and seeking for multiple or spare sources, or having their virtual water suppliers work closely. In this thesis, Chapter 8 conducts a case study to reveal the necessity to introduce economic instruments in order to deal with the water imbalance between water stress and virtual water flows exacerbated by economic trade among China's cities.

The other important pillar, social development, is in fact the outcome of economic growth. Social development also includes two aspects, one is about regional planning, and the other is related to residents' water environmental awareness. China still has a huge room for urbanisation as it is still in the second stage (Northam, 1979), and further development in this aspect would greatly benefit China's water sustainability with more efficient water use (Wu et al., 2012; Wang et al., 2019) (Chapter 9). In the meantime, increasing water environmental awareness among residents is also a key to the better management of China's household water use. In China, however, regions and cities might be at different development stages in the same period of time. In less-developed regions/cities, the main focus would still be enhancing residential awareness. In well-developed regions/cities, nevertheless, the bottleneck of further lowering household water use standards could be tackled by more sophisticated approaches such as introducing water-saving household appliances or promoting water-saving reward mechanism (Chapter 7).

Chapter 11 Conclusions

This chapter starts with summary of findings that clarifies how this thesis addresses its research questions. Then it is followed by contributions, innovation and added value of this thesis' empirical work, especially how academic arguments demonstrated in this thesis contribute to the existing academic literature. Finally, this chapter draws policy recommendations based on the policy landscape and the empirical work.

11.1 Summary of Findings

This thesis analyses the impact of China's economy and development patterns on its water scarcity and water pollution, with the attempt to propose countermeasures to mitigate the lack of water resources and the deterioration of water quality through the adjustment of economy and development patterns. In order to explicitly answer the main research question of this thesis "How could economy and development patterns be adjusted to alleviate China's water scarcity and water pollution?", this thesis raises four sub-questions:

(1) How China's water scarcity and water pollution across economic sectors on different scopes from production and consumption perspectives could be accounted?
Chapter 3 illustrates how this thesis compiles China's sectoral water datasets for various water quantity and water quality indicators (including water withdrawal, water use, NH_4^+ discharge and COD discharge) at both national and city levels, and these water datasets account physical water from the production perspective. In the meantime, Chapter 3 also explains how this thesis applies a great part of these water data in EEIOA to quantify embodied/virtual water in economic trade/supply chains from a consumption perspective.

(2) How the influences of China's economy and development patterns on its water scarcity and water pollution could be measured?
In Chapter 2, this thesis conducts a comprehensive literature review and highlights the advantages of water footprint studies. Hence, this thesis mainly establishes the relationship between water resources and economy, development patterns by adopting EEIOA (Chapter 6, Chapters 8-9). Besides, this thesis also explores the impact of economy, development on water issues by observing the spatiotemporal characteristics of water scarcity and water pollution as well as corresponding economy and development patterns simultaneously under specific policy context (Chapter 7).

(3) What positive and negative effects have economy and development patterns brought to China's water scarcity and water pollution over the past years?
This thesis incorporates four empirical cases to investigate the positive (Chapter 8 and Chapter 9) and negative (Chapter 6 and Chapter 7) influences exerted by China's economy and development patterns on its water status in small scales (BTH region (Chapter 6) and PRB (Chapter 7)) and in large scales (China (Chapter 9) and China's 313 cities (Chapter 8)) respectively. Based on the empirical results, positive and

negative effects brought by China's economy and development patterns on its water resources could be seen from the following perspectives:

Regional development is a key indicator determining the water utilisation of industries and economic sectors in China's regions. Great economic gap and development difference would compromise water equality in the regions. Besides, unclear division of responsibility among regions and cities would not only suppress their unique advantages but also cause the failure to achieve clustering effects/production scale in the regions and the cities. On the contrary, synergistic development and increasing cooperation would significantly optimise water management of multiple supply chains in the regions and the cities simultaneously.

In addition, economic trade greatly affects water resources distribution in supply chains among administrative units. Unripe economic trade market with untenable economic structure is likely to trigger or exacerbate water imbalance, especially the imbalance between water stress and water supply/use in administrative units. Conversely, a relatively mature economic trade market (both international and domestic markets) normally accompanies with increased competitive edges in the international market, domestic economic structure optimisation and technological advancement. The elimination of water-intensive and water-polluted industries and economic sectors, as well as the promotion of water environmentally-friendly industries and economic sectors would significantly alter China's water structure.

Moreover, social development also influences China's overall water sustainability. The process of urbanisation often brings a more advanced urban form and enables more urban areas to engage in water-saving and water-efficient production activities. Besides, a developed society would also cultivate environmental awareness among residents and household water use would be saved.

(4) What approaches are considered practical and effective to adjusting economy and development patterns to abate China's water scarcity and water pollution?
The empirical chapters (Chapters 6-9) of this thesis discuss how economy and development can be adjusted to alleviate China's water scarcity and water pollution on the basis of individual case studies. In addition, in Chapter 10, this thesis further examines the empirical results and has in depth discussions about potential approaches to achieving China's overall water sustainability. The approaches to alleviate water scarcity and water pollution via the adjustment of China's economy and development patterns could be seen as follow:

The upgrade and optimisation of economic structure is an ideal countermeasure to mitigate China's water scarcity and water pollution. This approach, however, includes more detailed measures:
(1) strengthening regional cooperation and promoting synergistic development could address uneven water distribution and inefficient water utilisation to a great extent, which then further saves water resources and improves the overall water quality. It is important that regions and cities in a region take advantages of their water-efficient pillar sectors based on their resources endowment and strong bases of their

advantageous sectors. And it is crucial that regions and cities with similar industrial structure could increase communication and deepen cooperation, especially allowing well-developed areas to exchange information/pass on practical experience about water-saving technologies with/to less developed places. In China, it is of great necessity to cultivate multiple water-efficient and environmentally-friendly industry leaders that adopt similar economic patterns.
(2) Proactively reacting to changes in international situation and making domestic policy enable China to better manage national water resources. When international situation changes, China could grasp the great opportunities to reform, especially regarding its export markets and outsourcing businesses. In the meantime, China could also release policies about domestic economic layout compatible with the economic transformation in the international market.
(3) Re-scheduling supply chains and economic trade patterns or introducing economic instruments related to water footprint concept could greatly optimise water structure. This approach requires a clear identification of key industries or economic sectors in the supply chain which have the greatest potentials to save water resources, to improve water efficiency, and to control water pollution. In addition, industrial and economic sectors heavily reliant on single sources of products that require huge amounts of embodied water could build mechanisms to avert water crisis and to combat water vulnerability by having its product importers reinforce communication with other industry leaders or simply by seeking for multiple product sources.

On the other hand, social development is also an important measure to alleviate China's water scarcity and water pollution. China could continuously accelerate urbanisation in order to enormously improve water efficiency across industries. When certain regions and cities enter relatively mature development stages, environmental awareness among residents could be raised to mitigate water issues in households.

11.2 Contributions and Innovation

Linking to this thesis' research gaps (Section 3.5), this section summarises the contributions of this thesis to the academic field from the theoretical, methodological, empirical and policy-related perspectives.

Theoretically, one of the biggest innovations of this thesis lies in its breakthrough made in China's city-level water footprint, with great attention paid to both water quality and water pollution. To begin with, this thesis focuses on China's water footprint studies, which greatly strengthen the understanding of the effects of economy and development on water scarcity and water pollution in the supply chain, especially the effects of trade as well as commodity production or consumption (Hoekstra and Chapagain, 2008). In comparison with other categories of studies about the relationship between economy, development and water management (Section 3.3), this thesis's water footprint analysis shows advantages in the following aspects: (1) It has a wider range of research scope instead of concentrating on water resources of certain links or specific industries in the supply chain. (2) Its spatiotemporal characteristics go beyond the research which solely focuses on the long-term trend of relationship between economy, development and water management, and could simultaneously investigate various geographical locations across time. (3) It does not need to deal with data mismatch triggered by different data natures of hydrological and socioeconomic factors. Regarding the research scope, this thesis conducts relatively comprehensive city-level water footprint studies in China, including a city-level water footprint research that covers China's 313 cities and a city-level water footprint research about water-energy nexus of thirteen cities in the BTH region. In the current research field, China's water footprint studies are more often at national and provincial levels, and limited city-level research only covers a few cities (mostly cities in well-known regions). This also applies to China's water-energy nexus in water footprint studies. Moreover, water footprint studies in this thesis examine both water quality and water pollution by adopting multiples water indicators, including water withdrawal, water use, NH_4^+ discharge and COD discharge. In the existing literature, China's water footprint research tends to explore water quantity and water scarcity indicators instead of water quality and water pollution indicators.

Besides water footprint analysis, this thesis also fills the absence of the existing literature by tracing water pollutants triggered by economy and development activities of all the cities within a river basin. Unlike hydro-economic accounting tools and watershed models (Section 3.3), this thesis clearly defines NH_4^+ discharge in the PRB from specific anthropogenic activities in surrounding administrative units/cities. Meanwhile, this thesis also explores more in-depth about spatiotemporal characteristics and dynamics of China's economy, development and water scarcity, water pollution, or their relationship under specific contexts/policy backgrounds. Compared with many studies which are only results-driven, the support of spatiotemporal analysis and policy backgrounds enable this thesis to offer a more comprehensive analysis.

Methodologically, this thesis fills the absence in the current filed by applying city-level environmentally extended input-output tables and compiling city-level water datasets. According to Section 3.3, EEIOA is considered as the most ideal method in the existing field to study the relationship between economy, development and water resources, but the lack of city-level environmentally extended input-output tables and city-level datasets constitute the major impediments to city-level EEIOA. This thesis overcomes this challenge and achieves the accomplishments in this regard by: compiling a dataset for water withdrawal of all the cities across individual economic sectors in China for the very first time (Section 4.1.1), and applying city-level multi-regional environmentally-extended input-output table in China's water footprint study for the very first time (Section 4.2.2). In addition, this thesis also compiles a dataset for NH_4^+ discharge of all the cities in the PRB for the very time in preparation for future city-level water footprint studies (Section 4.1.2).

From the empirical and policy-related perspective, this thesis only incorporates four case studies, which either cover a broad scale of research area (the whole nation, all the cities within the nation) or target at certain regions or cities (the BTH region, the PRB) but it chooses representative regions or cities with diverse characteristics. All types of cities are included in a region, service-based, high-tech oriented cities, or cities dominated in light-manufacturing and heavy manufacturing ((Shan et al., 2018). In this way, the empirical results and policy recommendations could be partly mirrored in other regions or cities at similar development stages.

11.3 Policy Recommendations

In Chapter 3, policy landscape analysis is clearly unfolded, which clearly directs which authorities should be referred to under different contexts. In combination with the previous empirical results (especially potential approaches of adjusting economy and development patterns to alleviate China's water scarcity and water pollution), this thesis puts forward some useful policy recommendations by proposing some economic techniques and development modes that could help further shape and guide China's water governance.

To start with, flexible water pricing and well-considered water subsidy are the most direct means of governmental intervention towards water/water-energy nexus management by giving financial support to less-developed administrative units or major water-intensive/water-polluted industries or economic sectors. Reduced water prices and added environmental subsidies then allow these administrative units or industries/economic sectors to invest in ecological remediation or in technological advancement (introducing cutting-edge water-saving equipment or water environmentally friendly raw materials). By clearly identifying key administrative units and industries/economic sectors, this thesis then offers suggestions for China's authorities to adjust water prices and appropriate environmental subsidies in these areas/industries/economic sectors.

The incorporation of the concept of water footprint into economic trade and supply chains could be secured by a key economic instrument: water rights trade. Given that virtual/embodied water flows often induce potential threats to China's water scarcity and water pollution, especially through supply chains in economic trade, the great attention should be paid to China's water/water-energy nexus footprint. Continuous promotion of water trading and water transactions with the utilisation of market mechanism and economic leverage enable China's authorities to allocate fairer environmental responsibilities for water use/pollution in specific industries and economic sectors. Nevertheless, China's current water rights trade market is not mature enough and lacks abilities to determine water rights buyers/sellers in water rights market based on factors of both water stress and virtual water flows embodied in trade. Therefore, in turn, this thesis greatly helps China's authorities to identify water rights buyers/sellers in specific industries or economic sectors among specific regions cities, which is the premise for the entry and the development of water rights trade market.

Although economic transformation is an ideal countermeasure to mitigate China's water scarcity and water pollution, the traditional paths might not suit each individual as an administrative unit has its own characteristics based on its resource endowment and industrial foundations. For example, the traditional transition from heavy- to light-industry or from agricultural- and manufacturing-orientation to service-orientation might not be applied in areas with abundant heavy metals or well-known agricultural- and manufacturing bases. Hence, this thesis explores some typical cases with concerns that call for China's authorities' prompt actions. For example, this thesis analyses agricultural sector in Urumqi and concludes that it has high water inputs but low economic yields. With the issue raised, China's authorities might be able to address the problem by paving a path for onward-oriented agricultural investment with businesses that involve agricultural services/e-commerce/finance and even genetic engineering instead.

Besides, this thesis also complies with the principles of development economics and circular economy, and suggests water management approaches. These approaches are grounded on these principles with the aim to achieve China's water sustainability. These approaches include but are not limited to: Urbanisation has brought more efficient water management but residents' environmental awareness needs to keep pace with the process of urbanisation continuously. Or any economic and regional planning should focus on long-term water benefits instead of short-term economic interests.

Appendices

Appendix A. Supplementary Materials

Table A1: 42 Economic Sectors

	Economic Sector		**Economic Sector**
S01	agriculture	**S22**	other manufacturing
S02	coal mining	**S23**	waste and flotsam
S03	petroleum and natural gas extraction	**S24**	product and equipment maintenance
S04	metal mining	**S25**	production and supply of electricity and heat
S05	nonmetal mining	**S26**	production and supply of gas
S06	food manufacturing and tobacco	**S27**	production and supply of water
S07	textile	**S28**	construction
S08	garment, leather, fur	**S29**	wholesale and retail
S09	wood and furniture	**S30**	transport and storage
S10	paper making, printing, stationery	**S31**	hotel and restaurant
S11	petroleum refining and coking	**S32**	Information transfer and software
S12	chemical product	**S33**	banking
S13	nonmetal product	**S34**	real estate
S14	metallurgy	**S35**	leasing and commercial service
S15	metal product	**S36**	scientific research
S16	general equipment	**S37**	water conservancy, environment, public facility
S17	specialist equipment	**S38**	resident service and other services
S18	transport equipment	**S39**	education
S19	electrical equipment	**S40**	sanitation and social welfare
S20	electronic equipment	**S41**	culture, sport, entertainment
S21	instrument and meter	**S42**	public management and social organisation

Table A2: Data Sources of the Water Withdrawal Dataset

Category	Indicator	Data Source
Primary Industry	Provincial- and city-level water withdrawal	China's provincial- or city-level statistic yearbook
	Irrigation areas	China's provincial-level statistical yearbook
	Irrigation water withdrawal per mu for farmland	China's water resource bulletin
Manufacturing Industry	Provincial- and city-level water withdrawal	China's provincial- or city-level statistic yearbook
	Industrial value-added	China's provincial- or city-level statistic yearbook
	Water withdrawal per industrial value-added	China's city-level water resource bulletin
	Sectoral industrial wastewater intensities of major enterprises	China high-resolution emission gridded dataset
	Sectoral industrial output	China's city-level statistic yearbook
Construction	Provincial- and city-level water withdrawal	China's provincial- or city-level statistic yearbook
	Flood space of housing	China's provincial-level statistic yearbook
	Water withdrawal per floor space of housing	Shanghai bulletin of the first census for water
Tertiary Industry	Provincial- and city-level water withdrawal	China's provincial- or city-level statistic yearbook
	Number of employees in hotel and restaurant	China city statistic yearbook
	Water withdrawal per employee in hotel and restaurant	Shanghai bulletin of the first census for water
	Number of employees in the other tertiary sectors	China city statistic yearbook
	Water withdrawal per employee in the other tertiary sectors	Shanghai bulletin of the first census for water
Household	Rural population	China's provincial-level statistic yearbook
	Household water withdrawal per capita in rural areas	China's provincial- or city-level statistic yearbook
	Urban population	China's provincial-level statistic yearbook
	Household water withdrawal per capita in urban areas	China's provincial- or city-level statistic yearbook

Table A3: Cities of Different Watersheds Zones in the PRB

Water Zone	City	Water Zone	City
The PRD	Guangzhou	Xijiang	Guilin
	Shenzhen		Chongzuo
	Zhuhai		Hechi
	Foshan		Wuzhou
	Jiangmen		Fangchenggang
	Huizhou		Guigang
	Dongguan		Yulin
	Zhongshan		Baise
Dongjiang	Shaoguan		Hezhou
	Heyuan		Laibin
	Ganzhou		Liupanshui
Beijiang	Shaoguan		Anshun
	Qingyuan		Qianxinan
	Zhaoqing		Qiandongnan
	Foshan		Qiannan
	Ganzhou		Kunming
Xijiang	Zhaoqing		Qujing
	Yunfu		Yuxi
	Nanning		Honghe
	Liuzhou		Wenshan

Table A4: Data Sources of the NH_4^+ Discharge Dataset

Category	Indicator	Data Source
Primary Industry	Provincial- and city-level NH_4^+ discharge	Annual statistic report on the environment in China China's city-level statistic yearbook
	Effective/gross weight of nitrogenous fertilisers	China's city-level statistic yearbook
Manufacturing Industry	Provincial- and city-level NH_4^+ discharge	Annual statistic report on the environment in China China's city-level statistic yearbook
	Industrial wastewater discharge	China's city-level statistic yearbook
	Sectoral industrial wastewater intensities of major enterprises	China high-resolution emission gridded dataset
	Sectoral industrial output	China's city-level statistic yearbook
	National standards between industrial wastewater discharge and industrial NH_4^+ discharge	China's environmental statistic
Construction	Sewage in construction, secondary industry	China's city-level water resource bulletin
Household	Provincial- and city-level NH_4^+ discharge	Annual statistic report on the environment in China China's city-level statistic yearbook
	Domestic sewage, water use, water supply	China's city-level statistic yearbook

Table A5: Data Sources of the Water Use and COD Discharge Dataset

Category	Indicator	Data Source
Water Use	Total water use in primary industry and manufacturing industry, Total domestic water use	China water resource bulletin
	Sectoral manufacturing industrial water use	Annual statistic report on the environment in China
	Average ratios of water use in construction, tertiary industry, household	China's provincial- and city-level water resource bulletin and statistic yearbook
	Number of employees in tertiary sectors	China statistic yearbook
COD Discharge	Total COD discharge in agriculture, Total domestic COD discharge	Annual statistic report on the environment in China
	Sectoral manufacturing industrial COD discharge	Annual statistic report on the environment in China
	China's total population	China statistic yearbook
	China's total employee numbers	China statistic yearbook
	Number of employees in tertiary sectors	China statistic yearbook

Table A6: 4 Provinces and 309 Cities in the 2015 City-level Multi-Regional Input-Output Table, and their Regional Divisions

Regional Division	Provinces and Cities
North China	Beijing, Tianjin, Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang, Hengshui, Taiyuan, Datong, Yangquan, Changzhi, Jincheng, Shuozhou, Jinzhong, Yuncheng, Xinzhou, Linfen, Lvliang, Huhhot, Baotou, Hulun Buir, Hinggan, Tongliao, Chifeng, Xilingol, Ulanqab, Ordos, Bayannur, Wuhai, Alxa
Northeast China	Shenyang, Dalian, Anshan, Fushun, Benxi, Dandong, Fuxin, Liaoyang, Panjin, Tieling, Chaoyang, Huludao, Jinzhou, Yingkou, Changchun, Jilin, Siping, Liaoyuan, Tonghua, Baishan, Songyuan, Baicheng, Yanbian, Harbin, Qiqihar, Jixi, Hegang, Shuangyashan, Daqing, Yichun, Jiamusi, Qitaihe, Mudanjiang, Heihe, Suihua, Greater Khingan Range
East China	Shanghai, Nanjing, Wuxi, Xuzhou, Changzhou, Suzhou, Nantong, Lianyungang, Huai'an, Yancheng, Yangzhou, Zhenjiang, Taizhou, Suqian, Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing, Jinhua, Quzhou, Zhoushan, Taizhou, Lishui, Wenzhou, Hefei, Wuhu, Bengbu, Huainan, Maanshan, Huaibei, Tongling, Anqing, Huangshan, Chuzhou, Fuyang, Suzhou, Luan, bozhou, Chizhou, Xuancheng, Fuzhou, Xiamen, Sanming, Quanzhou, Zhangzhou, Nanping, Longyan, Putian, Ningde, Nanchang, Jingdezhen, Pingxiang, Jiujiang, Xinyu, Yingtan, Ganzhou, Jian, Yichun, Fuzhou, Shangrao, Jinan, Qingdao, Zibo, Zaozhuang, Dongying, Yantai, Jining, Taian, Weihai, Rizhao, Laiwu, Linyi, Dezhou, Binzhou, Heze, Weifang, Liaocheng
Central China	Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Anyang, Hebi, Xinxiang, Jiaozuo, Puyang, Luohe, Sanmenxia, Nanyang, Shangqiu, Xinyang, Zhumadian, Jiyuan, Xuchang, Zhoukou, Wuhan, Huangshi, Shiyan, Yichang, Xiangyang, Ezhou, Jingmen, Huanggang, Xianning, Suizhou, Enshi, Xiantao, Xiaogan, Jingzhou, Shennongjia, Tianmen, Qianjiang, Changsha, Zhuzhou, Xiangtan, Hengyang, Yueyang, Changde, Yiyang, Chenzhou, Yongzhou, Huaihua, Xiangxi, Loudi, Zhangjiajie, Shaoyang
South China	Guangzhou, Shaoguan, Shenzhen, Zhuhai, Shantou, Foshan, Jiangmen, Zhanjiang, Zhaoqing, Huizhou, Meizhou, Shanwei, Heyuan, Yangjiang, Qingyuan, Dongguan, Zongshan, Chaozhou, Jieyang, Yunfu, Maoming, Nanning, Liuzhou, Guilin, Wuzhou, Fangchenggang, Qinzhou, Guigang, Yulin, Baise, Hezhou, Hechi, Laibin, Chongzuo, Beihai, *Hainan*
Southwest China	Chongqing, Chengdu, Zigong, Panzhihua, Luzhou, Deyang, Jinyang, Guangyuan, Suining, Neijiang, Leshan, Nanchong, Meishan, Guang'an, Ya'an, Ziyang, Ganzi, Yibin, Dazhou, Bazhong, Aba, Liangshan, Guiyang, Liupanshui, Zunyi, Anshun, Bijie, Tongren, Qiandongnan, Qiannan, Qianxinan, *Yunnan*, *Tibet*
Northeast China	Xi'an, Tongchuan, Baoji, Xianyang, Weinan, Yan'an, Hanzhong, Yulin, Ankang, Shangluo, Lanzhou, Jiayuguan, Jinchang, Baiyin, Tianshui, Wuwei, Zhangye, Pingliang, Jiuquan, Qingyang, Dingxi, Longnan, Linxia, Gannan, *Qinghai*, Yinchuan, Shizuishan, Wuzhong, Zhongwei, Guyuan, Urumqi, Kelamayi, Tulufan, Hami, Changji, Ili, Altay, Bortala, Bayingol, Aksu, Kashgar, Hotan, Shihezi, Kizilsu Kirghiz, Tarbagatay

Table A7: Sectoral Classification in Chapter 5

S04	ferrous mining, nonferrous mining
S06	agriculture by-product, food, beverage, tobacco
S08	garment, leather and fur
S12	chemical materials, pharmaceutical manufacturing, chemical fibre, rubber and plastic
S14	ferrous metallurgy, nonferrous metallurgy
S30	automobile manufacturing, manufacturing of railway, shipping, and aviation industry
S22	other manufacturing, utilisation of the waste product
Except for the above-mentioned sectors, the other sectors remain the same as S2-S27 in Table A1.	

Table A8: Sectoral Classification in Chapter 6

Economic Sector		**Economic Sector**	
agriculture	S01	**utilities**	S25-S27
mining	S02-S05	**construction**	S28
food	S06	**sales**	S29
textile	S07-S08	**transport**	S30
chemical	S12	**hospitality**	S31
metal & nonmetal	S13-S15	**Info. & finan.**	S32-S35
prod. equip.	S16-S20	**resid. service**	S38
other manuf.	S9-S11,S21-S23	**pub. service**	S36-S37, S39-S42

Table A9: Sectoral Classification in Chapter 7

Economic Sector		**Economic Sector**	
agriculture	S01	**electronic equipment**	S20
food & tobacco	S06	**electricity & gas & water**	S25-S27
textiles & garments	S07-S08	**other manufacturing**	S02-S05,S11,S21-24
wood & paper	S09-S10	**construction**	S28
chemicals	S12	**hotels & restaurants**	S31
metal & nonmetal products	S13-S15	**education**	S39
general & specialist equipment	S16-S17	**sanitation**	S40
transport equipment	S18	**public management**	S42
electrical equipment	S19	**other services**	S29-S30,S32-38,S41

Appendix B. Abbreviations and Acronyms

Bt(s) — billion tonne(s)

BTH — Beijing-Tianjin-Hebei

CCETE — China Carbon Emission Trade Exchange

CNY — Chinese Yuan

CIOA — Chinese Input-Output Associate

COD — Chemical Oxygen Demand

CPC — Communist Party of China

CPI — consumer price index

CSC — China Science Communication

DIN — Dissolved Inorganic Nitrogen

DIP — Dissolved Inorganic Phosphorous

E — eutrophication index

EEIOA — Environmentally Extended Input-Output Analysis

EKC — Environmental Kuznets Curve

EORA — The Eora Global Supply Chain Database

FAO AQUASTAT — Food and Agriculture Organisation of the United Nations AQUASTAT

GBA — Guangdong-Hongkong-Macao Greater Bay Area

GCE — General Computable Equilibrium

GDP — Gross Domestic Product

Global NEWS — Global Nutrient Export from Watershed Model

GOV — The Central People's Government of the People's Republic of China

GTAP — Global Trade Analysis Project

GWLF — Generalised Watershed Functions

LCA — Life Cycle Assessment

IDA — Index Decomposition Analysis

IOA — Input-Output Analysis

Kt(s) — thousand tonne(s)

LMDI — Logarithmic Mean Divisia Index

MEP — Ministry of Ecology and Environment of the People's Republic of China

MREEIOA — Multi-Regional Environmentally Extended Input-Output Analysis

Mt(s) — million tonne(s)

MWR — Ministry of Water Resources of the People's Republic of China

NBS — National Bureau of Statistics

NH_4^+ — ammonia nitrogen

NH_3-N — unionised ammonia

NH_4^+-N — ionised ammonia

NO_2-N — nitrite nitrogen
NO_3-N — nitrate nitrogen
NPC — National Pollution Census
OEC — The Observatory of Economic Complexity
OECD — Organisation for Economic Co-operation and Development
PBR — Pearl River Basin
PPI — producer price index
PRD — Pearl River Delta
UN — United Nations
UNICEF/WHO — United Nations Children's Fund/World Health Organisation
USD — United States dollar
WBG — World Bank Group
WEF — World Economic Forum
WEST — Water Economy Simulation Tool
WFN — Water Footprint Network
WOID — World Input-Output Database
WRI — World Resources Institute
SEEAW — System of Environmental-Economic Accounting for Water
SD — System Dynamics
SDG — Sustainable Development Goal
SGCC — State Grid Corporation of China
SPARROW — Spatially Referenced Regressions on Watershed attributes
SREEIOA — Single Regional Environmentally Extended Input-Output Analysis
SWAT — Soil and Water Assessment Tool

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