UNIVERSITY OF EAST ANGLIA

Methods and Accounts for Water Withdrawal at the City Level and Evaluation of Sectoral Water Saving in China

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Acknowledgements

‘*It's time to see what I can do; To test the limits and break through;*

…

Here I stand and here I'll stay; Let the storm rage on…’

-- lyric of <*Let it go*> from theme song of <*Frozen*>, Disney

On the night of 13th September, 2017, when I put my first step on the ground of Norwich, I was fearful and lonely: I would spend a long time in the UK for the first time in my life, a new horizon so distant away from my home in mainland China. Now, as I'm approaching the final stage of my PhD study, I am a fully engaged person and achieving the best of myself-with no fear in my heart anymore.

My PhD study is in a split-site program joint with Southern University of Science and Technology in China (SUSTech). Over the past four years (April 2017- April 2021), I have been co-supervised by Prof. Dabo Guan and Prof. Junguo Liu. Approaching the final stage of my PhD study, I am grateful of taking this special and joint PhD program and dual-education system. As a 4th year PhD student, I feel peace in my heart and hope to make a big progress.

Thank Dabo for sharing view of life and teaching me a philosophy of *enduring multi-tasks under a changing atmosphere*. In detail, Dabo had systematic and thorough discussions about outline and draft of thesis, teaching me whether topics or foci were innovative and appealing or not. He is so considerate and responsible to help me find experts whose work are related to territory and administrative water management (in China) and scholars who have related work about water stress. I sought their wisdom and followed his instructions to elaborate this research. He provided me with data-materials and inspired my interest and enthusiasm in my research, no matter how busy

he was. For example, I still remember an opportunity he gave to participate in a national point-sourced survey, covering various sectors and enterprises of China in July 2017. Additionally, he has encouraged me to tease out my puzzles, look at different perspectives and fight hard before multiple deadlines. Many times, I was amazed at how many questions he raised and thought about, with a vision in advance by decades. This makes me feel like devoting myself into scientific research for its very essentials, and helps me to find my orientation in my own way. At last in this way, he raises me up. Many thanks for all his enormous efforts in managing the process and arrangements.

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At last, as it goes ‘what does not kill you makes you stronger’, I should also thank myself for integrity. My dean told me that a UK PhD candidate should be 1) self-motivated and 2) well-prepared. In my hometown, a PhD degree is an honor. For long I aimed to pursue it and put constant efforts. It continuously brings me motivations to

inspire self-examination. Being eager to learn, I myself usually devote long time making much concordance about data. I collated and verified nearly every single figure in statistical yearbooks and water resources bulletins. For example, focusing on nearly 23,000 data in 2015 (all 343 prefectures in China multiplying 65 sectors in each prefecture), if there is any figure not concordant, I would calibrate and reconcile them one by one, for days and for nights. Although I still see limitations in current research, I could promise to myself no false data under currently possible conditions. As a result, I learnt to pay careful attention to major problems and relax control over small ones, then develop wisdom (courage) and carry on. Only through this time-consuming and patience-demanding process, could I thoroughly clean statistical materials. Every single bit of progress achieved should be beneficial for China's water management.

Many times, I doubted and encountered weakness of myself facing trick and adversity of PhD study. I need to break down and rebuild outline, logic and detailed-meanings, meanwhile overcome many difficulties. These are throughout my PhD study. Along the way, I understand meaning of critical thinking and develop ability to solve continuous and hybrid problems. Adversity is a good discipline. I am doing my best to have luck seizing November opportunity of graduation.

Many thanks for viva examiners, Prof. Helen He and Prof. Gordon Mitchell, because they have helped me to recall every bit about why and how I conducted this PhD thesis and similar work. Additionally, their timely responses have earned time for my study. Thanks to Gordon's criticism: he has shared his philosophy and taught me a lesson of integrity. I would keep his guidance in mind. Besides, Gordon has asked some questions I never thought about, which inspired me looking into surface, for example those on the most cutting-edge water saving options under an international context. As an expert,

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I am aimed to write my thesis in a concise yet systematic way. The ending is an initial step. Finger crossed.

Zongyong Zhang

PhD Achievements (outputs)

Forthcoming Work:

Zongyong Zhang, Yuli Shan, Martin Tillotson, Philippe Ciais, Hong Yang, Zhao Zeng, Dandan Zhao, Xian Li, Bofeng Cai, Dabo Guan*, Junguo Liu*. High-resolution water accounts show targeted sectors under '*Redline Regulation*' of China. under review in contributed to Nature Geoscience.

Zongyong Zhang, Yuli Shan, Bofeng Cai, Xian Li, Dabo Guan*, Junguo Liu*. City-level water withdrawal, availability and scarcity accounts of China in 2015. under review in Scientific Data.

Publications:

Zongyong Zhang, Junguo Liu*, Bofeng Cai, Yuli Shan, Heran Zheng, Xian Li, Xukun Li, Dabo Guan*. (2020) City‐Level Water Withdrawal in China: Accounting Methodology and Applications. Journal of Industrial Ecology, 24, 5, 951-964. (SCI, IF=6.5)[1]

Zongyong Zhang, Junguo Liu*, Kai Wang, Zhan Tian, Dandan Zhao. 2020. A review and discussion on the water-food-energy nexus: Bibliometric analysis (in Chinese). Chinese Science Bulletin. 张宗勇，刘俊国*，王凯，田展，赵丹丹. 水−粮食−能

[1] This is a jointly-authored publication used in this thesis (1/2).

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Mo Li, Thomas Wiedmann*, Junguo Liu*, Yafei Wang*, Yuanchao Hu, **Zongyong Zhang,** Michalis Hadjikakou. (2020). Exploring consumption-based planetary boundary indicators: An absolute water footprinting assessment of Chinese provinces and cities. Water Research, 184, 116163. (SCI, IF=9.13)

Xian Li, Yuli Shan, **Zongyong Zhang,** Lili Yang*, Jing Meng*, Dabo Guan. (2019). Quantity and quality of China's water from demand perspectives. Environmental Research Letters, 14(12), 124004. (SCI, IF=6.1)

Heran Zheng, **Zongyong Zhang,** Zengkai Zhang, Xian Li, Yuli Shan, Malin Song, Zhifu Mi, Jing Meng*, Jiamin Ou, Dabo Guan*. (2019). Mapping carbon and water networks in the north China urban agglomeration. One Earth, 1(1), 126-137. (Cell press)

Xian Li, Lili Yang, Heran Zheng, Yuli Shan, **Zongyong Zhang,** Malin Song, Bofeng Cai, Dabo Guan. (2019). City-level water-energy nexus in Beijing-Tianjin-Hebei region. Applied Energy, 235, 827-834. (SCI, IF=8.8)[2]

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[2] This is a jointly-authored publication used in this thesis (2/2).

labor supply? An empirical analysis based on 112 cities in China. Journal of Cleaner Production, 190(JUL.20), 378-387. (SCI, IF=7.25)

Zongyong Zhang, Yu Hao*, Zhinan Lu, Yuxin Deng. (2018). How does demographic structure affect environmental quality? Empirical evidence from China. Resources Conservation and Recycling. (co-1st author) (SCI, IF=8.1)

Conference Proceedings and Presentations:

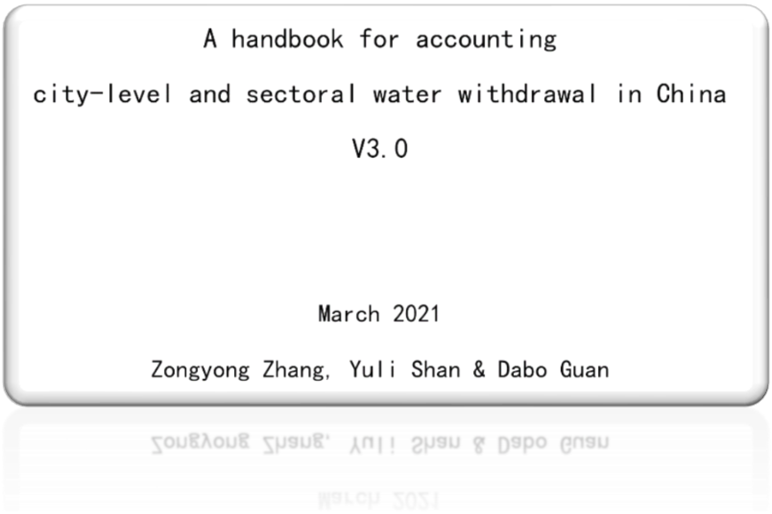
Zongyong Zhang, Junguo Liu, Yuli Shan, Bofeng Cai, Heran Zheng, Xian Li, Dabo Guan. (2018) Water accounts in China. **Applied Energy Summer School 2018**, Beijing, China. Oral presentation.

Zongyong Zhang, Junguo Liu, Bofeng Cai, Yuli Shan, Heran Zheng, Xian Li, Xukun Li, Dabo Guan. (2018) The city level water use accounts in China: methodology and applications. **'City+ 2018': The international conference for young researchers on urban studies**. London, UK. Poster.

Zongyong Zhang. (2019) Sustainability in cities: environment-energy-socioeconomic nexus. **Applied Energy Summer Seminar 2019**, Beijing, China. Coordinated and Attended.

Zongyong Zhang, Yuli Shan, Dabo Guan. (2018-2021) A handbook for accounting city-level and sectoral water withdrawal in China. **Applied Energy Summer School**

2018-2019, Beijing, China. Oral presentation and discussion.


A handbook for accounting
city-level and sectoral water withdrawal in China
V3.0

March 2021
Zongyong Zhang, Yuli Shan & Dabo Guan

Figure 1 A screenshot of a manual for accounting city-level and sectoral water withdrawal in China. (Note: this handbook is to support implementation of water accounting framework in this study)

Zongyong Zhang. (2018) **Water security workshop with water@Leeds.** Water Security Research Centre, UEA. Attended and discussed.

Heran Zheng, **Zongyong Zhang,** Xian Li, Yuli Shan, Malin Song, Zhifu Mi, Jing Meng, Jiamin Ou, and Dabo Guan. (2018) Carbon and Water Chain in Sustainability for North China Urban Agglomeration. **'City+ 2018': The international conference for young researchers on urban studies**. London, UK. Oral presentation.

Zongyong Zhang. (2017). **'City+ 2017': The international conference for young researchers on urban studies**. Cambridge, UK. Attended and discussed.

Zongyong Zhang, Junguo Liu, Kai Wang, Zhan Tian, Dandan Zhao. (2020) A review and discussion on the water-food-energy nexus: bibliometric analysis. **American Geophysical Union-Fall Annual Meeting 2020**, Online (intended San Francisco, U.S.). Poster presentation and discussed.

Zongyong Zhang, Junguo Liu, Kai Wang, Zhan Tian, Dandan Zhao. (2019) A review and discussion on the water-food-energy nexus: bibliometric analysis. **International symposium on water-energy-food nexus, The 10th national conference on environmental chemistry, 10th NCEC**, Nankai University, Tianjin, China. Oral presentation.

Zongyong Zhang. (2018) **Tyndall research strategy for consultation in the next 5 years.** Tyndall Research center, UEA. Attended and discussed.

Scholarship and others:

2017-2021 Postgraduate research studentships, joint-supervised PhD Program between University of East Anglia and Southern University of Science and Technology.

I have served journals as a reviewer in the field, including Applied Energy (SCI, IF=8.8), Journal of Cleaner Production (SCI, IF=7.3), Structural Change and Economic Dynamics (SSCI, IF=2.0).

Participation of Research Projects:

Project supported by the National Science Foundation for Distinguished Young

Scholars of China, Water resources assessment in hybrid natural-economic systems: theory and methodology of Water Resources Assessment for Natural-Economic Systems, 41625001, 2017/01-2021/12, under research, participated.

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Working papers:

Zongyong Zhang, Dabo Guan, et al.. Methodology of water consumption and water withdrawal datasets among developing countries along One-belt and One-road regions.

Zongyong Zhang, Cunxue Zhao, et al.. Temporal and spatial change and heterogeneity of water use in China: a provincial analysis.

Zongyong Zhang, Jinjun Xue, et al.. Inequality of water use among sectors: review and empirical analysis

Zongyong Zhang, Junguo Liu, Dabo Guan, et al.. Large uncertainties of water use and efficiency among ISIMIP models and data

Zongyong Zhang, Rui Cai, et al. Environmental Kuznets curve of water use among Chinese cities

Abstract

In the context of the freshwater crisis, two-thirds of the cities in China suffer from freshwater scarcity, and there are restrictions on the use of water by industries. Although '*Redline Regulation*' policies as core regulations were set to save water through improving water-withdrawal efficiency, China still has transnationally low efficiency owing to poor sectoral water-saving initiatives. Control on efficiency still lacks targeting and prioritization to specific sectors and cities.

To save water at the city level has become a priority strategy of regulation and requirement in water field for China, yet how to conduct and realize it among various cities or sectors has not been fixed. Although high water-consumption activities are proposed in a few cities, comparison across the whole cities and economic-sectors could not be realized. Accounting for sectoral water withdrawal at the city level could help planners regulate water use in different sectors to improve water use efficiency. Thus, high-resolution water accounting methods and datasets in terms of spatiality and economic-sector are critical for China's water saving. What is more, it is meaningful to investigate sectoral water-saving potential and implication for alleviating scarcity, to promote sustainable water use and economic development.

Yet due to lack of measured efficiency data, there remains a dearth of water withdrawal accounting methods and datasets, as well as water availability and scarcity data, no matter for total or sectoral amounts for prefectural cities. These data limitations from water statistics and accounting in China are significant, long-lasting for two decades (typically data from 1995 are still being utilized in research, and urgently need to be updated).

Compared to developed countries, such as Australia etc., water accounting in China has already fallen behind. Disaggregated sectoral water withdrawal accounting is not readily available for China. Not all cities in China have the water accounting as 'routine' management activities. Approximately one fifth of 343 cities do not collect or develop water data statistics (with no bulletins). For data of the other four fifths of cities, there are only total numbers of six types provided (with differences in terms of statistical calibers etc.). New accounting methodology is needed to develop, which should be suitable for new cases according to specific statistical conditions of different sectors, and China's own actual state. This is quite different from developed countries. Water withdrawal statistics in China are patchy, and water data across all sectors at the city level appear to be relatively insufficient.

Hence, in administrative and territorial scopes, I develop a general framework to, for the first time, account for water withdrawal of 65 economic-social-environmental sectors in cities of China. This novel methodology is based on water withdrawal efficiency, as benchmark performance, from point-sourced surveys in China (led and carried out by the Ministry of Ecology and Environment) in 2015. It features in selection of 22 driving forces, and I connect each size indicator with its unique water-withdrawal efficiency. The general framework is applied because only inconsistent water statistics collected from different data sources at the city level are available.

Applying this general framework, I account for water withdrawal of all 65 economic-socio-environmental sectors for all 343 prefectural cities in China, using a 2015 data benchmark. Then I compare different scopes and methods of official accounts and statistics from various water withdrawal datasets. I further account for total water availability, and water scarcity status in each of 343 prefectures. These high-resolution water accounts in terms of spatiality and economic-sector are unprecedented in China.

From the water withdrawal datasets, I first find 1) different from conventional perceptions that agriculture is usually the largest water user, industrial and household water withdrawal may also account for the largest percentages in the water-use structure of some cities, for example Luoyang (central) for industrial water withdrawal; and Guangzhou (south) and Qingdao (east) for household water withdrawal. 2) The difference among annual household water use per resident in the urban areas of different cities is relatively small (as is the case for rural areas), but that between urban and rural areas is large. Thus, increased attention should be paid to controlling industrial and urban household water use in particular cities, such as Xi'an (west), Shaoxing (east), Taizhou (east), Luoyang (central), and Chongqing (southwest).

These high-resolution water scarcity accounts throw light upon cities suffering from water scarcity, and low water-efficiency sectors at the city level: I find 3) agricultural and industrial sectors with high water-withdrawal intensity exist in representatively small developing cities. 4) The top 10% of low-efficiency industrial sectors represent 46% industrial water withdrawal. Examples of 3) and 4) are listed below: papermaking and product manufacturing in Chenzhou (central), Lincang (southwest) and Qiqihar (northeast); liquor, beverage and tea manufacturing in Jingdezhen (mid-east), Anqing (mid-south) and Wuzhou (southwest); electricity and hot water supply in Changde (mid-south); and agricultural-related sectors in Zhoukou (central), Linyi (east) and Fuyang (mid-south). Thus, attention should also be paid to both coordinating production scales in water-scarce cities, and reducing water withdrawal intensities for stringent management.

What is more, to investigate sectoral water-saving potential and implication for alleviating stress, I build water-saving scenarios in 41 industrial and 5 agricultural sectors across 180 water-scarce cities, by assuming a convergence of below-average efficiencies to the national sector-average for technology improvement.

I find overall industrial water-withdrawal efficiency could improve by 20%, satisfying the redline regulation. 18.9 km^3 (±3.2%) water saving in industry and 50.3 km^3 (±2.3%) in agriculture would be achieved, equivalent to the annual water demand of Russia. A minority of sectors could contribute to most water savings whilst minimizing economic disruptions. In contrast, implementing water efficiency measures in the majority of sectors would result in significant economic change to achieve identical savings. As a result, water efficiency improvements should be targeted towards this minority of sectors: cloth(ing) and chemical manufacturing in industry, and rice, vegetables and fruits cultivation in agriculture. Cities with above-average water saving potential are Suzhou (south), Nanjing (southeast), Xiangtan (mid-south), Guangzhou (south) and so on for industry; Bayannur (north), Kashi (northwest), Akesu (northwest), and Daqing (northeast) etc. for agriculture.

There would be 18 cities with population of 40 million alleviated below the scarcity threshold (40%) and shake off water scarcity at identical water availability levels, for example Xining, Zhangye, Hotan, Haidong (northwest), Jincheng, Yulin (west), Jilin city (northeast), Wuxi and Xiangtan (mid-south). At the national level, mean scarcity level of water-scarce cities would fall by 20 percentage points from 96% to 76%, being alleviated to sub extreme-scarcity level.

Through unique account, I propose that sectoral water saving should be well positioned to alleviate water stress, through improving sectoral water use efficiency, especially by reducing sectoral water withdrawal intensities with little cost to the economy. I think sectors of low efficiency in water scarce cities should be well-targeted. Requiring all sectors to evenly or in-general improve water efficiency does not represent an optimal policy choice. In sum, this complete analysis through unique account would bring a conceptual advance.

Our results help to enable targeted saving strategies and identify priorities, to facilitate more effective water regulation through optimizing efforts for improving efficiency. At last, these geo-data of high resolution could be used directly in input-output models, consumption-based accounting and structural decomposition analyses. The data accounted would facilitate proceeding to in-depth exploration. Data could also help gain in-depth insights, concerning sectoral water withdrawal, and alleviating water stress from local activities.

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Chapter 1 Introduction

1.1. China's water crisis and nation-wide *'Redline Regulation'*

Freshwater is an essential and global resource (Zeitoun 2011; Wada et al. 2014b; Gleick et al. 2004; Showstack 2013). The water resource per capita in China is only one-quarter of the world average, and China was identified as high shortage, measured with per capita blue water availability approximately 910 m^3 per year in northern China in 2018, below the recommended global baseline for water scarcity (1,700 m^3/year) (Zhang et al. 2020a), by a Falkenmark indicator[3] (Falkenmark et al. 1989; Falkenmark and Widstrand 1992; Chapagain and Hoekstra 2008). In 2005, Falkenmark indicator of north China plain is less than 500 m^3/cap/year (Liu et al. 2017) as 'absolute shortage'. In 2020, Falkenmark indicator of north China plain is still lower than Israel in the international context.

Meanwhile, rapid economic growth in China has led to large amounts of water use. Over the last 50 years, China's industrial and agricultural water withdrawal increased in 90% of its cities (Zhou et al. 2020), and have remained at high levels above 126 and 369 km^3/yr from 2013 to 2018 (The Ministry of Water Resources 2019). China has become the largest water user by total amount (Piao et al. 2010), compounding the adverse impacts of water pollution on water resource availability (Liu et al. 2017; Li et al. 2019a). As a result, two-thirds of the cities in China suffer from freshwater scarcity

[3] If water availability falls below 1,000m^3/cap/year, then the area experiences high water scarcity, and below 500m^3/cap/year, absolute scarcity (Falkenmark et al. 1989; Falkenmark and Widstrand 1992). In reference (Chapagain and Hoekstra 2008), water scarcity indicator was defined as the national water footprint divided by the country's total renewable water resources from 1997-2001.

(Qiao and Liu 2014), and there are restrictions on the use of water by households and industries, even in non-arid areas. It is predicted that the water-use crisis in China will gain increasing attention (Zhao et al. 2012) due to reports that water demand in China will exceed the water supply by approximately 2030 (Shifflett et al. 2015). Explanations could be unbalance supply and demand, i. e., insufficient supply vs. quite-high demand.

To save water and alleviate water stress, the Chinese State Council legislated specially for industrial and agricultural water withdrawals through the so-called '*Redline*' regulations on water withdrawal amount and efficiency , as a water-quantity part of *the 'Most Stringent Water Resources Management System'* nationwide since 2011 (Liu et al. 2013), through reducing industrial withdrawal per value-added by 20%, and irrigation utilization-coefficient in farmland by 0.02 between 2015 and 2020. At the same time, total and annual water withdrawal amount should be controlled less than 700 billion m^3 from 2015 to 2030. Among the national 700 billion m^3, each province has been assigned its own quota since 2017.

The '*redline*' regulations are core strategies followed by other national and main policies under China's water resource management context. An in-depth summary of water resources management processes in China was shown in Table 1. Overall speaking, 1) demand management options are dominant, and there is few supply-side policies; 2) emphases of water conservation have extended from water quality (before the 12^{th}-five-year plan, i. e., 2010-2015), to water quality, water quantity, and water ecosystem equally (since the 13^{th}-five-year plan, 2016-2020). For example, more recently, to improve water use efficiency and address water-saving, China established national demonstration *'sponge'* cities to reduce extensive water use and conserve water by 2030 (Kuang et al. 2018; Jiang et al. 2018). Production and economic development have to be closely based on local water availability. The *Ministry of Water Resources* and local *Hydrology and Water Resources Investigation Bureaus* would issue access licenses for water withdrawal.

The *Ministry of Water Resources* and local *Hydrology and Water Resources Investigation Bureaus* (data collector) are responsible for developing water data statistics (mainly water resources bulletin), and local *Hydrology and Water Resources Investigation Bureaus* are data collectors. Although these *Hydrology and Water Resources Investigation Bureaus* are quite common and unified, no matter at the province, city or county level, China's official accounting is still quite broad or general with a much-weak quality, compared to developed countries.

Reasons why water withdrawal and use statistics are so poor could be threefold: a) awareness for water withdrawal and use statistics are weak because in some places water is regarded as a nearly-free resource and withdrawn unlimitedly. In their daily perception, some people from water-sufficient areas even will not pay for water, including drinking water. b) there is no full basis for statistics due to no sufficient meters (as stated in detail in the second paragraph of section 1.2) or large-scale survey. Due to lack of measured efficiency data, data collectors or publishers were not able to disaggregate total amount. c) some collectors are fear to reveal water use data: in China, some officials with responsibility for water use may feel pressure to reveal water-use data to the public because these data are included in the performance evaluation system for political promotion, and they care about their own achievement. For details, see in References (https://time.com/3848171/china-environment-promotions/). At last, in terms of evaluation for policies and plans, basically this part is quite loose and usually conducted or reflected by the authorities and governments themselves.

To date, water resources redline regulation of China merely sets and controls a total amount, with no specific targets or requirements at the city level to realize it. There were few practical measures before 2016, because this regulation was mainly a requirement to be assigned to sub-country level during this period. Since 2016, following ‘redline’ regulations, *double control actions* were to stress more practical measures, and *double control actions* added detailed requirements (quotas) on total-amount and water-withdrawal-efficiency at the province level by 2020 (At the city or county level, some provinces did disaggregate requirements (quotas) to the lower one (city) or two (county) levels, yet some provinces did not do these down-scale assignments. But all information of these disaggregated requirements (quotas) was not available to public.). *Double control actions* are prepared for practical measures to stress and continue ‘redline’ regulations. In 2017, among the national 700 billion m^3 by 2030, each province has been assigned its own quota. There are not any probable practical measures until early 2018. Due to release of sponge city, building nationwide water-saving demonstration cities, and an outline document on drafting and promoting water-saving law and standard (National initiative and action for water saving in 2019), these polices bring state power to force practical measures. These specifical measures include

a) Education: in China, education for saving water starts from preliminary school, with many science-popularization classes taught by professors from higher-level universities. Propaganda about saving water could be seen in most places;
b) Economic: multi-tier pricing plan and increasing water price (please refer to detailed discussion in Question No.7#);
c) Administrative: restrictions on use of water by households (by fixing a limited time period) and industries (by setting a limited total amount), even in non-arid areas.

Nevertheless, these measures were not efficiently implemented, or of little effect. Low-efficiency problem has not yet been solved: water withdrawal per GDP (10^4 yuan) was 60.8 m^3, still higher than 50 m^3 of the USA and Japan etc. developed countries; and water withdrawal per industrial value-added (10^4 yuan) was 38.4 m^3 till 2019 (The Ministry of Water Resources 2019). The 'eco-system' of water initiatives in China is complex; process in this regard is rather slow.

Table 1 China's water quantity policy from 2010 to 2020: main national regulation summary

Regulation	Year	Conferences	Major Targets	Details by 2030
Three Red Lines (core strategies)	2011	The No.1 Document and the highest-level national conference on water conservancy	Control total amount of water withdrawal	National annual water withdrawal not exceed 700 billion m^3; to promote water-right trade
			Increase water withdrawal efficiency	Water use value added below 4.0 m^3 /10^3 yuan
			Set a pollution discharge limit of water function zones	*Ratio up to standard of water quality* in function zones should reach 95%
Double control actions	2016	To stress following '*redline*' regulations, it added detailed requirements (quotas) on total-amount and water-withdrawal-efficiency at the province, city and county levels; To continue '*redline*' regulations		
Sponge city	Early 2018	To build nationwide water-saving demonstration cities; To continue '*redline*' regulations		
National initiative and action for water saving	2019	To release an outline document following '*redline*' regulations; It set up law and standard, market-mechanism; To continue '*redline*' regulations		

In a word, to save water at the city level has become a priority strategy of regulation and requirement in water field for China, yet how to conduct and realize it among various cities or sectors has not been fixed. Although high water-consumption activities are proposed in a few cities, comparison across the whole cities and economic-sectors could not be realized.

1.2. Low water use efficiency due to lacking targets on sectors and cities to save water

Although '*Redline Regulation*' policies were set to save water through improving water-withdrawal efficiency, China still has transnationally low efficiency owing to poor sectoral water-saving initiatives (Howell 2001; Deng et al. 2006; Cheng and Li 2021). Control on efficiency still lacks targeting and prioritization to specific sectors and cities. Although the '*Redline Regulation*' policies were set early in 2011, efficiency problem has not yet been solved. Water withdrawal per GDP (10^4 yuan) was 60.8 m^3, still higher than 50 m^3 of the USA and Japan etc. developed countries; and water withdrawal per industrial value-added (10^4 yuan) was 38.4 m^3 till 2019 (The Ministry of Water Resources 2019).

A draft was not proposed until June 2015, and only a few cities had begun installing and improving water meters to record full water-withdrawal since December 2017 in western China, for agricultural irrigation amount (clearly stated in the 2019 *National Initiative and Action for Water Saving*) (The Ministry of Water Resources 2019; Zhang et al. 2020b). In China, currently using metering is basically limited to a part of large users, and conventional meters are not sufficiently equipped. Notably, if the volume of water withdrawal is uncertain, it is difficult to regulate water demand, let alone eliminate the over extraction of water and assess the intensity of water use (such as the water consumption per industrial value added or the irrigation efficiency coefficient). The implicit volume of water withdrawal and water intensity creates more uncertainty and places constraint on sustainable economic development (Chen et al. 2020a; Qi et al. 2020).

What's more, water-use efficiency of China is still low transnationally, partly owing to mis-management (Shifflett et al. 2015; Kong et al. 2016; Lal 2015; Wang et al. 2020), specifically poor sectoral controls and water-saving initiatives (Zhao et al. 2016). Control on water withdrawal intensities and volumes still lacks targeting and prioritization to specific sectors (Jiang et al. 2018).

1.3. Urgent requirement for high-resolution water accounting methods and datasets

Due to lack of measured efficiency data, there remains a dearth of sectoral water withdrawal accounting methods and datasets, as well as water availability and scarcity data, no matter for total or sectoral amounts for prefectural cities (including leagues, regions and autonomous prefectures). This data limitation from water statistics and accounting of China is significant and exists for long (even some latest data are not updated and remain in 1995 in the current research, which should be brought up to date). Compared to developed countries, such as Australia, America and France (Vardon et al. 2007; Brandt 2001; Baynes et al. 2010), water accounting in China has already fallen behind. Water withdrawal statistics in China are patchy, and water data across all sectors at the city level appear to be relatively insufficient. Accounting for sectoral water withdrawal at the city level could help planners regulate water use in different sectors to improve water use efficiency. Thus, high-resolution water accounting methods and datasets in terms of spatiality and economic-sector are critical for China's water saving.

Hence, in administrative and territorial scopes, I developed a general framework to, for the first time, estimate the water withdrawal of 65 economic-social-environmental sectors in cities in China. This novel methodology was based on water withdrawal efficiency, as benchmark performance, from point-sourced surveys in China in 2015. It featured in selection of 22 driving forces and I connected each size indicator with its unique water-withdrawal efficiency. The general framework was applied because only inconsistent water statistics collected from different data sources at the city level are available.

Under this general framework, I accounted for water withdrawal of all 65 economic-socio-environmental sectors for all 343 prefectural cities in China, using a 2015 data benchmark. (I first applied it to 18 representative Chinese cities then expanded to all 343 prefectures.) Then I compared different scopes and methods of official accounts and statistics from various water withdrawal datasets. I further accounted for water availability, and water scarcity status by total in each of 343 prefectures. These high-resolution water accounts are unprecedented in China and throw light upon cities suffering from water scarcity, and low water-efficiency sectors at the city level. In sum, these geo-data of high resolution facilitate proceeding to in-depth exploration.

1.4. Targeted sectors and cities for efficiency improvement are central to save water

Through unique high-resolution water accounts, I proposed that sectoral water saving should be well placed to alleviate water stress, by improving sectoral water-use efficiency, especially by reducing sectoral water-withdrawal intensities with a little cost to economy, to finally promote sustainable water use and economic development. I think sectors of low efficiency in water scarce cities should be well-targeted. Requiring all sectors to evenly or in-general improve water efficiency does not represent an optimal policy choice. In sum, this complete analysis through unique account would bring a conceptual advance. The results help to enable targeted saving strategies and identify priorities, to facilitate more effective water regulation through optimizing efforts for improving efficiency.

This cross-disciplinary study will stimulate discussion and enable policy and technology interventions amongst industrial and agricultural sectors on water saving potential in China. I also think this research will generate wider academic and practitioner interest worldwide. In summary, this primary research is an initial step to test knowledge limits and break through for China water statistics and accounting science. I think this would appeal to the broad range of the community across the economic-activity base of 65 industrial sectors.

1.5. Research aim, objectives, and framework

1.5.1. Research aim and objectives

Research aim is to promote sustainable water use and economic development.

Objective 1: <u>to develop **methods** for sectoral water withdrawal at the city level.</u>

Objective 1a: to quantify water withdrawal at the city level (in sections 3.1. 3.2 and 3.3 of Chapter 3) (by collating and estimating sectoral water withdrawal data);

Objective 1b: to help planners know (in sections 4.1 and 4.2 of Chapter 4), assess water use (in sections 5.1 and 5.2 of Chapter 5), and evaluate how to regulate water use in different sectors (in section 5.3 of Chapter 5 and in sections 6.3 and 6.4 of Chapter 6).

Objective 2: to build up **accounts** and datasets of high-resolution: account for sectoral water withdrawal and water scarcity for prefectural cities.

Objective 2a: to identify water-stressed cities and low water-efficiency sectors at the city level (in sections 5.1 and 5.2 of Chapter 5);

Objective 2b: to study how to save water (in sections 5.3 of Chapter 5 and 6.1-6.2 of Chapter 6) (I suggested sectors of low efficiency in water scarce cities should be well-targeted to save water, under the *'Redline Regulation'* of water withdrawal efficiency improvement).

Objective 3: to propose **sectoral water saving** strategies (in 5.3 of Chapter 5 and 6.3(.1-.2) of Chapter 6) (through unique account, I proposed that sectoral water saving should be well placed to save water in water scarce cities).

Objective 3a: to analyze how to improve sectoral water-use efficiency by reducing sectoral water-withdrawal intensities with a little cost to economy (in sections 6.1, 6.2 and 6.3 of Chapter 6);

Objective 3b: to address how to target to sectors and cities (in 6.4 and 6.5 of Chapter 6 and 7.1 and 7.2 of Chapter 7) (I suggested sectors of low efficiency in water scarce cities should be well-targeted, rather than requiring all sectors to evenly or in-general improve water efficiency).

In sum, objectives 3a-3b are achieved 1) to investigate sectoral water-saving potential and implication for alleviating scarcity; 2) to help enable targeted saving strategies and identify priorities; and 3) to facilitate more effective water regulation through optimizing efforts for improving efficiency and water stress alleviation. Eventually, these objectives (1a-3b) are to promote sustainable water use and economic development (i. e., for *research aim* above).

1.5.2. Research framework and thesis structure

Research framework is illustrated in Figure 2.

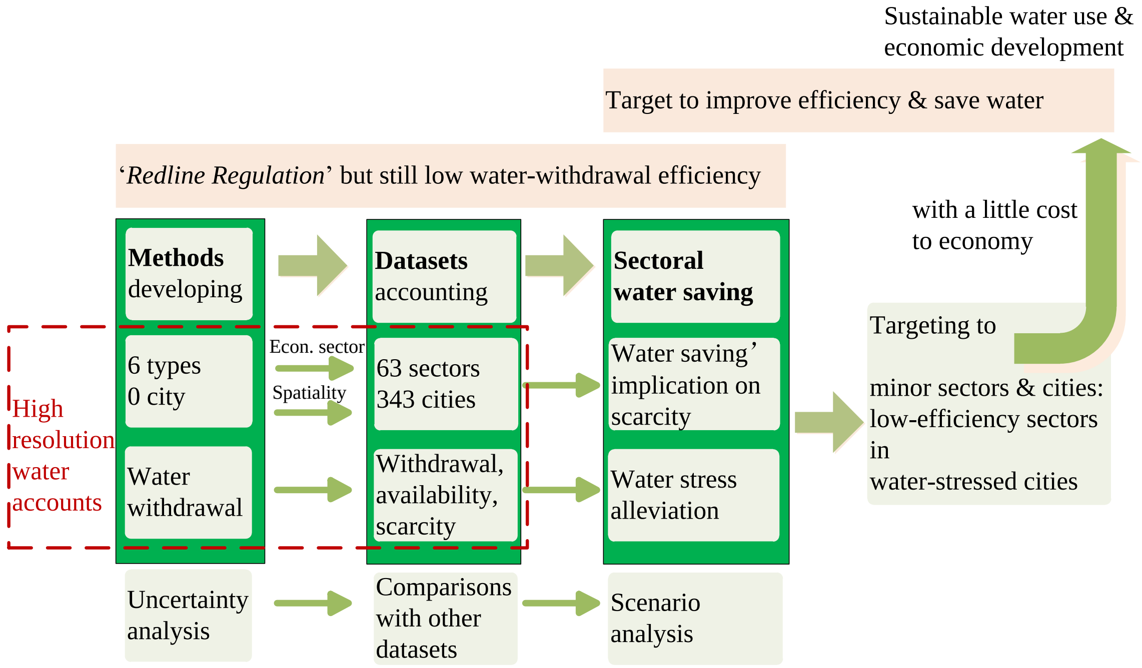

Figure 2 Research framework of PhD study

Logically, Chapter 1 is introduction chapter, with section 1.4 intended to be a closing section: it summarizes sections 1.1-1.3 (as well as a summary on result and finding of the thesis). Specifically, it justifies why it is central to target sectors and cities for efficiency improvement and water saving.

Chapter 2 is literature review. I reviewed water withdrawal, availability and scarcity accounting methods and accounts. For water withdrawal, beginning approaches and accounts, administrative and territorial methods and accounts, and sectoral methods and accounts are reviewed respectively. For water availability and water scarcity, I introduce accounting approaches and scopes. Then I supplement literature on evaluation of water saving potential. I find research gaps in threefold: 1) high-resolution water withdrawal accounting methods and accounts in terms of spatiality and economic-sector in China; 2) prefectural water availability and scarcity accounts in China; 3) sectoral water saving potential with targets on specific sectors and cities.

In chapter 3, I propose a general methodology for establishing a water inventory for all economic-social-environmental sectors in prefectural cities in China. I disaggregate agriculture, industry, construction, service, household and environment into 65 subsectors. Collating and estimating sectoral water withdrawal data at the city level is a basic first step toward increasing water conservation. This chapter ends with uncertainties analysis.

Chapter 4 reports the datasets of water withdrawal, availability and scarcity for China's prefectures in 2015. Under the general framework, I accounted for water withdrawal of all 65 economic-socio-environmental sectors for all 343 prefectural cities in China, using a 2015 data benchmark. I first applied it to 18 representative Chinese cities then expanded to all 343 prefectures and obtained datasets.

More importantly, in Chapter 5, through the high-resolution water scarcity accounts I first identified water-stressed cities and low water-efficiency sectors at the city level. These sectors of low efficiency in water scarce cities should be well-targeted to save water, under the *'Redline Regulation'* of water withdrawal efficiency improvement. Through unique account, I proposed that awareness of sectoral water savings should be given greater focus in water scarce cities to prevent the situation to get worse.

Chapter 6 is scenario analysis. Based on high-resolution accounts, I built scenarios assuming a convergence of below-average efficiencies to the national sector-average for technology improvement, to explore water-saving potential amongst industrial and agricultural sectors respectively, and implication for alleviating water stress of Chinese cities under constraint of the intensity-reduction redline. I proposed that sectoral water saving should be well placed to alleviate water stress. For key sectors and cities, the results help to enable targeted saving strategies and identify priorities, to facilitate more effective water regulation through optimizing efforts for improving efficiency.

Chapter 7 concludes with a summary of methodological novelty for high-resolution water withdrawal accounting in China; and a summary of results and key findings in twofold: 1) prefectural water withdrawal and stress accounts by sector and total; 2) sectoral water saving in targeted cities, followed by limitations and future research.

Table 2 below shows the notations and abbreviations used in the following parts of PhD thesis.

Table 2 Notations and abbreviations in alphabetical order

Notations & abbreviations	Meaning
Agri. based cities	Agriculture-based cities
CHRED	China High-Resolution Emission Gridded Datasets
CR	Criticality ratio, to measure annual water scarcity (%)
FAO	Food and Agriculture Organization
Employment	Number of employees (person)
Energy prod. cities	Energy production cities
Flospac	Floor space of housing (m^2)
GDP	Gross domestic products (100 million yuan)
GIS	Geographic information system
Greenarea	Urban area of green land, to estimate ecosystem & environment water withdrawal (m^2)
Heavy manf. cities	Heavy manufacturing cities
i (subscript)	i represents a city

IPCC	Intergovernmental Panel on Climate Change
Irriareas	Irrigation area (mu, mu is Chinese acre, 1 mu≈667 m^2)
k (subscript)	k represents a sector of city *i*
n (subscript)	n represents total number of cities
NAQSIQ	National Administration for Quality Supervision & Inspection & Quarantine
NBS	National Bureau of Statistics, P.R. China
Output	Disaggregated & sectoral industrial output of each sector, to divide total industrial water withdrawal in each city (100 million yuan)
Popul	Rural or urban population, permanent residents (10^4)
Sanitarea	Environmental sanitation areas, to estimate ecosystem & environment water withdrawal (m^2)
UN	United Nations
Valueadded	Total industrial value added (100 million yuan)
WA	Water availability, annual renewable freshwater resources amount (10^4 m^3)
$Water_{i,\,k}$	Water withdrawal of sector *k* in city *i* (10^4 m^3)
$Water_{i,\,UrbanPublic}$	Urban & public water withdrawal, composed of water withdrawal from construction, accommodation & catering & other services (10^4 m^3)
WaterIndus	Total industrial water withdrawal in each city (10^4 m^3)
WW	Water withdrawal (10^4 m^3)

Chapter 2 Literature review

For water withdrawal, according to China Water Resources Bulletin (The Ministry of Water Resources 2019), water withdrawal is a newly withdrawn water amount allocated to end users. It includes leakage and loss for transportation. Yet due to data unavailability at the city level and large scale, I assumed no water leakage or loss for transportation in this study.

In current China-related statistical materials, 'water withdrawal' equals to 'water use' for farming, forestry, animal husbandry, fisheries, construction, service, household, and ecosystem and environment preservation; only for industry, 'water use' equals to sum of 'water withdrawal' and 'reused water'. Thus, in this study based on China-related statistical materials, the term 'water use' is a generalized definition, and it is only distinguished from 'water withdrawal' for industry (i. e., for industry, we only account for water withdrawal). Notably, in other Chinese research, both calibers (the generalized term and water withdrawal) are used. At last, I also noticed, and must acknowledge that in Chinese language situation, difference is ambiguous, unless one uses 'net water use', which is identical with the meaning of 'withdrawal' used in foreign studies, i. e., demand minus losses (e.g., leakage) and non-consumptive use. Yet there is a dearth of statistics or materials on this regard. One possible reason may be that those Chinese materials mostly stress differences from demand to supply, and the term of 'demand' is meant for a part from total supply.

Besides, I regard water use the same as water demand (quantity demanded amount). For water consumption, I was intended to focus on this indicator at the beginning of this PhD study, however, there is few statistical data available. For water withdrawal efficiency in this study, agriculture's water-withdrawal efficiency was measured with agricultural water withdrawal per irrigated area. Industry's water-withdrawal efficiency was measured with industrial water withdrawal per output.

In this study, water availability is annual renewable freshwater resources amount. It is from local precipitation within a city and calculated as surface water amount plus groundwater minus the amount with duplicate measurement. Annual water scarcity is measured with criticality ratio (%), i.e.: water withdrawal to availability ratio. Criticality ratio connects anthropogenic water withdrawal with natural water quantity. It takes into consideration environmental flows (Vörösmarty et al. 2010; Liu et al. 2016) and natural biodiversity (Kirby et al. 2014).

In this study, water accounting means statistic and estimation for water withdrawal (total and sectoral), availability, and water withdrawal-to-availability ratio (as a measurement for physical and quantitative water scarcity) at the city level. There is no detailed number from the supply side. Generally, in this study, water withdrawal, water availability, and water scarcity are accounted by total for each city. Then I disaggregate total water withdrawal into 65 sectors in each city.

2.1. Water withdrawal accounting methods and accounts

As put in the literature, high-resolution data are critical for sustainable water management (Wang et al. 2020); and water withdrawal data are among the most sought (Gleick et al. 2004; Showstack 2013). Although the earliest water accounting studies appeared in the late 1950s, this field truly began to develop in the 2000s and has become somewhat popular in only the last decade, yet the number of studies especially under

China’s context is still relatively small, and China has fallen behind in this regard.

Actually, satellite measurements or monitored data have only been limitedly applied or used. For total water withdrawal accounting, due to incomplete installation of metering or other gauging facilities in various sectors, estimations based on quota have been combined with metering in some cities for two decades before 2020. Similarly, for some water withdrawal efficiencies or coefficients from estimations of water resources bulletin, end use metering is preferable to use. In case metering or monitor is only limitedly applied or used due to incomplete installation of metering or other gauging facilities, estimations based on quota have been combined with metering in some cities.

For current literature, I found ‘monitored data’ and ‘modelled estimates’ may be not independent or separated from each other. In case metering or monitor is only limitedly applied or used due to incomplete installation of metering or other gauging facilities, simulations have to be combined with metering in some areas. For example, in China monitored data have only been limitedly applied or used for total water withdrawal accounting. Due to incomplete installation of metering or other gauging facilities in various sectors, estimations based on quota have been combined with metering in some cities for two decades before 2020.

2.1.1. Early approaches and accounts

Although Nace (1971) provided methods to record water use and establish commonly used accounting frameworks, it did not provide information on sectoral water use at any level.

In the recent three decades, the California Federation (CALFED) program in the USA was developed in the Sacramento-San Joaquin Delta of California to record water use (CALFED 2018). This program originated in 1990 and developed over the next two decades. The CALFED program identified and managed specific water withdrawal to leave enough water for threatened fish species[4]. This is important because it generated a consensus on the need for timely and critical water withdrawal numbers that has become a regulatory baseline (CALFED, 2018). Based on this result, Brandt (2001) and Brown et al. (2009) continued to use this program to designate water demand for fisheries from 2001 to 2005 in the USA.

2.1.2. Review on administrative and territorial methods and accounts

An important type of study, focused on hydrological models, simulates sectoral water use (Veldkamp et al. 2017; Wada et al. 2014b; Flörke et al. 2013). For example, H08 hydrological model (Dalin et al. 2014) was used in FAOSTAT to simulate water withdrawal of 4 types of crops and 3 types of livestock for China in 2005; waterGAP (Flörke et al. 2013) simulated domestic and industrial water withdrawal simultaneously at the global scale, nevertheless their spatial resolution was a bit low. Additionally, some researches acquired water withdrawal data in water-quality modules of hydrological models (Veldkamp et al. 2017; Hanasaki et al. 2012; Van Vliet et al. 2017). Besides, some simulations on carbon emissions (Liu et al. 2020b) chose

[4] It is an early study relevant to environmental flow requirement. In my PhD study, water withdrawal for ecosystem and environment preservation includes grassland irrigation, deep well injection, environmental sanitation and improvements, and **the supplementation of rivers, lakes, and marshes**. Although some studies show it is still to be determined (Liu et al. 2021), I think this part of water withdrawal could supplement environmental flow requirement, as CALFED program did.

topography, temperature and so on as proxy indicators to separate total amounts.

However, these are usually in a geographic grid unit rather than based on an administrative-territory basis (Wada et al. 2011; Huang et al. 2018). For example, with satellite measurements and monitored data, Karimi et al. (2013) investigated net water withdrawal processes for different land-use groups, and eventually provided comprehensive water datasets under 'WA+ framework' to summarize an overall water resources situation for global complex river basins. Although grids can be clipped to the administrative boundary by using GIS etc., many problems including inconsistence would arise (Zhang et al. 2020b; Yamada 2015; Chen et al. 2018), because calculations, methods or mechanisms they applied may be different from administrative and territorial accounting. There are a few studies in administrative and territorial scopes, including worldwide, nation-wide, provincial and prefectural levels in total:

Hoekstra and Chapagain (2006) estimated national water use of different countries from a production base, by introducing agricultural water use efficiency as a factor on water consumption. A few institutions provided national and sectoral water withdrawal data, such as AQUASTAT from the Food and Agriculture Organization (FAO). At the province and megacity level, Zhao et al. (2010) and Liao et al. (2020) employed Input-Output (IO) method to account sectoral water consumption. Similarly, Feng et al. (2012) accounted sectoral water footprints from a consumption perspective.

These data were nevertheless too general to be partitioned into more disaggregated prefectural-cities. For prefectural and territorial scopes, only a few data could be accessed (Zhou et al. 2020). Only Zhou et al. (2020) provided total water withdrawal data for multiple years through simulations based on survey and statistic data of

Ministry of Ecology and Environment. Yet some data-source information is hard to review or trace back, due to partial release of information and conservative sensitivity of government about water issues. Some original survey and data could be regarded as state secrets in China. These caused challenges and difficulty of data comparability, quality and reflection. For details, please refer to section 3.3.2 where I used this study for a validation and discussion. Besides, they commonly regard construction, services and households as a single sector called domestic water use (Alcamo et al. 2003), which omits water withdrawal information and difference of finer sectors in construction, services and households. Actually, water withdrawals of construction and services account for approximately one fifth of total domestic water withdrawal on average (Zhang et al. 2020b).

2.1.3. Review on sectoral methods and accounts

Overall speaking, the related research has evolved from including only a few sectors at the primary stage to the current accounts, which contain most economic-social-environmental sectors.

Regarding the methodologies of specific-sector studies, interdisciplinary researches including physical, hydrological as well as economic methods are used (Li et al. 2020). Baynes et al. (2010) used an integrated framework of stock and flow calculators in the water production sector and summarized the calibers of historical water accounting systems. Okadera et al. (2015) focused on machining processes, including turning, milling, drilling, and cooling. Cazcarro et al. (2010) was based on a disaggregated social accounting matrix of Huesca in Spain. Mitchell (1999) forecast industrial and commercial water consumption by 2025 using econometric method in the Yorkshire

Water Services Ltd. region; Williamson et al. (2002) developed econometric model of annual district level domestic water consumption, respectively. Similarly, Nawaz et al. (2019) forecast household water consumption for the Thames Water region to 2100. Mitchell et al. (2000) addressed the other water consumptive uses. Water inventory in this study was based on customer metering and divided by economic activity, using the Standard Industrial Classification. It also shows that sectoral water inventory accounting has been a routine part of water resources planning.

However, these investigations are limited to a few processes rather than for all sectors in the economy of a territory. Disaggregated sectoral water withdrawal accounting is not readily available for China. Not all cities in China have the water accounting as 'routine' management activities. Approximately one fifth of 343 cities do not collect or develop water data statistics (with no bulletins). For data of the other four fifths of cities, there are only total numbers of six types provided (with differences in terms of statistical calibers etc.). New accounting methodology is needed to develop, which should be suitable for new cases according to specific statistical conditions of different sectors, and China's own actual state. This is quite different from developed countries.

Thus, detailed water withdrawal in other sectors is rarely provided, indicating that these investigations are insufficient for exploring local water issues (Liu et al. 2016). In addition, these water accounting calibers also suffer from high variation, as they select different water sources (i.e., surface water, groundwater, and tap water) because the statistical water data in question were largely incomplete and only water withdrawal in part of a region or from a few kinds of water supply sources could be accessed.

Additionally, some industrial-ecology research applies life-cycle-based methods outside China, such as Owens (2001) and Berger and Finkbeiner (2013), but China's water data are usually insufficient to apply the same method (Lin et al. 2012). For example, sectoral water withdrawal, and water consumption data are unavailable or not made public, other than some gross types of water data at the national, provincial and city levels. Such data before 2013 of early years are even less. Although published by the National Bureau of Statistics of China, some data such as sectoral industrial output at the city level are not reliable (Chow 2006), and need further calibration or concordance with other public data. AQUASTAT has also collected agricultural, industrial, and municipal water withdrawal for China and other nations (FAO, 1998; FAO, 2019). However, due to lack of sectoral surveys to obtain water withdrawal efficiency as benchmark performance in China, they fail to disaggregate these water data into subsectors.

To date, compared to developed countries, such as Australia, America and France (Vardon et al. 2007; Brandt 2001; Baynes et al. 2010), water accounting methods and accounts in China has already fallen behind in the field of sectoral methods and accounts (Zhang et al. 2020b). Sectoral water accounts have been established in several countries at the national level, e.g., Australia, Denmark, France, the Netherlands, New Zealand, Spain and the U.S. (Maupin et al. 2014). These methods and accounts usually align with *Global Reporting Initiative* frameworks to develop their own framework in a rigorous manner. Although each nation delivers its accounts differently, there is some similarity in terms of the structure and scope of water accounting, which is formalized in Stadler et al. (2018) and the handbook on the System of Environmental and Economic Accounting for Water Resources (UN, 2006). For example, Stadler et al. (2018) was based on satellite accounts for resource consumption. For China it has 26 classified accounts by 200 products (sectors). I basically comply with such defaults.

Here I took America and Australia as examples and showed the state-of-the-art of current water accounting. In the U. S., to address considerable fragmentation of water accounting methods, CEO water mandate is aimed for ability for all to measure and communicate water in a consistent way (https://seea.un.org/sites/seea.un.org/files/ungc_cwaf_presentation_june_25_2019_0.pdf). It proposes and promotes the most cutting-edge water topics, such as urban and local water use information disclosure from large enterprises, water valuation, and return on investment, etc., to improve resilience of water. Nevertheless, none of these topics are discussed or spread in China.

Similarly, Australia's water account is also one of the famous programs and presents water-use information from 2000 to 2016 in Australia (Australian Bureau of Statistics, 2016). Specifically, Australia has water accounting framework in the mining and metals industry (https://minerals.org.au/water-accounting-framework-australian-minerals-industry). Without this accounting method or framework, approaches on measuring, monitoring and reporting on water use were often inconsistent between sites within enterprises or across sector. To address this inconsistence, a water accounting framework for Australian minerals industry has been developed since 2005 by University of Queensland Sustainable Minerals Institute. For more than six years' revision, exploration and accumulation thereafter, this framework was adopted as a common industry approach to water accounting. In other words, it could be easily adapted to a range of local contexts, based on given benchmark performance on water withdrawal efficiency.

Yet Australia program still suffers from a few problems: for example, 1) its data sources are disparate and originate from many different institutions, agencies and departments

(Australian Bureau of Statistics (ABS), 2004), as it has been stated that '*over a hundred sources of data were used in the second ABS Water Account'* (p. 51, ABS, 2004). 2) this program omits disaggregated information for construction, services, and environmental water use, as well as detailed industrial splits. 3) the data are incomplete and occasional due to the intermittent information used in early provisions (Baynes et al. 2010).

2.2. Water availability and scarcity accounts

2.2.1. Water availability accounting approaches and scopes

An early study by Begemann and Libby (Begemann and Libby 1957) was related to a continental inventory of groundwater; however, because their inventory was only used as one of the factors to analyze water circulation patterns worldwide, datasets were 1) non-transparent and incomplete; 2) simulated in a grid unit rather than territory.

There are mainly three indicators in the current study: net runoff (the local water resources, i. e., locally generated runoff), natural streamflow (the local and upstream natural streamflow taking account of the environmental flow requirements (EFR)), and natural streamflow minus consumptive use from upstream human activities (the local and upstream natural streamflow taking account of upstream consumptive water withdrawals and EFR) (Liu et al. 2019b). Water resources bulletins (The Ministry of Water Resources 2019) and Liu et al. (2019b) uses the net runoff measure. Specifically, water availability was annual renewable freshwater resources amount. It was from local precipitation within a city[5], and calculated as surface water amount plus groundwater minus the amount with duplicate measurement[6]. These indicators are from a supply side. They were shown in Equation (1). In China, their corresponding numbers are reported directly in water resources bulletins, issued by the *Ministry of Water Resources* and local *Hydrology and Water Resources Investigation Bureaus*. This water availability was equated to sum of surface runoff and precipitation recharge (The Ministry of Water Resources 2019). Surface water amount was natural runoff in surface water body such as, rivers, lakes and reservoirs. Groundwater volume was directly drained and recharged by precipitation and surface water body (The Ministry of Water Resources 2019).

$$Water\ availability_i = Surface\ water_i + Groundwater_i - Duplicate\ amount_i \quad (1)$$

where *i* represents a city.

Note that, first, water availability from the Water resources bulletins (The Ministry of Water Resources 2019) and Liu et al. (2019b) did not include entry of water[7] from upstream rivers, and water transfer projects (such as the South-to-North water diversion

[5] I did not take into account evaporation here. Consideration of water availability here is based on supply side (where water comes from); evaporation etc. belong to demand side, i. e., where water goes. Thus, it should make sense not to take into account evaporation here.
[6] In certain Karst areas, some surface rivers are converted into underground flows (rivers). Or some underground rivers are converted into surface rivers. These are how conversions between surface water and groundwater occur. When total water availability amount is calculated, if duplicate amount is not deducted, it would lead to repeated calculations on water amount.
[7] Here I did not use a term ‘inflow’. As far as I understand, inflow may be a bit broader than 'entry of water'. Besides, the choice of this indicator is mainly due to better data availability and simplicity. This should be a limitation of this study, considering that water use largely relies on water resources from upstream river network, especially where local water resources are scarce. Data for the South-to-North water transfer is not readily available to the public, I could only get a few from the middle route of the South-to-North water transfer projects. This should be supplemented in future work.

project), i. e., this availability amount was merely from local precipitation. This is due to unavailable data. For entry of water, while flowing through a city, a certain part does become surface water or groundwater as leakage etc., yet this quantification is uncertain and still under-researched (because measurement is subject to specific circumstances of a hydrological cross-section). This was a significant difference of research in administrative and territory units (Zhao et al. 2019), from research in river basin units (Liu et al. 2019b).

Second, water availability from the Water resources bulletins (The Ministry of Water Resources 2019) and Liu et al. (2019b) did not consider re-supplement amount from irrigation, due to a lack of data. This indicator did not include return flow from irrigation. For China's water availability research, there is a difference in terms of measuring water availability in the current literature: Due to data unavailability, most domestic research in China don't incorporate return flow (The Ministry of Water Resources 2019) while foreign (overseas) studies out of China include this part (National Research Council 1999; Hanasaki et al. 2012; Wada et al. 2014b). Thus this study may have underestimated water availability.

To sum, about water availability measurement, generally there are lots of simulation in a grid unit (Wada et al. 2011; Flörke et al. 2013; Alcamo et al. 2003; Alcamo and Henrichs 2002). In this aspect, many studies are especially for China (Cai 2008; Cai and Rosegrant 2004; Liu et al. 2019b). Nevertheless, there are few in a territory unit.

2.2.2. Quantitative water scarcity accounting approaches and scopes

Although nation-wide China is deficient in water (Liu et al. 2008), with a wicked problem between water withdrawal and availability (Shifflett et al. 2015; Liu et al. 2020a), city-level water scarcity has not been fully accounted for (Liu et al. 2019b). The science of water scarcity assessment has developed for the past 30 years and, as more spatial geo-data have been available, studies have adopted more integrated and multi-faceted approaches typically based on spatial resolution in grid units at the river basin scale (Gao et al. 2018; Wang et al. 2016) or global levels (Liu et al. 2017; Veldkamp et al. 2017; Flörke et al. 2013), rather than at administrative and territory based units such as the city level. For example, Liu et al. (2019b) stressed growing water stress in China from the past (1971-2010), to the future (2021-2050) periods.

However, in China city is a basic decision-making and regulation unit for almost all principal policies. There is only a single city-level based study in 2005 from the Ministry of Water Resources in China, which is not widely available to the public (Anon 2018). Thus far, to the best of my knowledge, an appraisal of cities and their water scarcity status is unavailable. Only Liao et al. (2020) accounted water scarcity footprint in six megacities of China and found heavy (84%) dependence of comprehensive scarce water on importation. In a sectoral perspective, these demands were mainly from coal, electricity and petroleum from specific locations.

In terms of measuring scarcity, Falkenmark indicator is a famous measurement for water shortage, with per capita renewable water resource, nevertheless, it did not reflect the environmental flow requirement (Rijsberman 2006; Liu et al. 2017). The criticality ratio (water withdrawal to annual renewable freshwater) is a simple and classical indicator of blue water (surface fresh water, i.e., water in rivers, lakes and reservoirs) and quantitative scarcity (Alcamo et al. 2000; Oki 2006). Yet it has thus far not been applied at the city level (Zeng et al. 2013; Liu et al. 2017; Zhao et al. 2015; Cai et al.

2017), due to data limitations (Wang et al. 2020). For example, Zhao et al. (2015) applied the criticality ratio (%) to measure annual water scarcity in Eq. (2), i.e.:

$$Criticality\ Ratio_i = Water\ withdrawal_i / Water\ availability_i \qquad (2)$$

where *i* represents a city; water availability included surface water and groundwater (precipitation into local territory as stated above [8]). Criticality ratio connects anthropogenic water withdrawal with natural water quantity. It takes into consideration environmental flows (Vörösmarty et al. 2010; Liu et al. 2016) and natural biodiversity (Kirby et al. 2014).. The higher the ratio is, the more stress is placed on available water resources from withdrawal, and the greater the probability of water scarcity occurrence (Alcamo and Henrichs 2002). Over-40% criticality ratio is generally accepted as high water scarcity status; and over-100% ratio is regarded as extreme scarcity.

About economic water scarcity, IWMI indicator combined physical and economic water scarcity, with proportion of water supply that is water availability, accounting for water infrastructure (Seckler et al. 1998; Liu et al. 2017). Yet given relatively sufficient water infrastructure and investment, I find economic scarcity may be not that common under China's context.

To sum, about water scarcity measurement (Veldkamp et al. 2017; Wada et al. 2014a), a lot of literature discussed and updated indicators for water stress index, especially,

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[8] Surface water comes from two sources: 1) precipitation into a local territory; 2) import via river flow. This availability includes part 1), but does not include part 2).

the ratio of water withdrawal to water availability (natural streamflow minus upstream consumptive water withdrawals). These review and gaps are preparation for extended applications at the city level of previous methods.

2.3. Evaluation of water saving options and potential in China

Overall speaking, in China, to save water is a priority national strategy for water resources, underlying national regulations such as the most stringent water resources management policy (i. e., red lines for total and annual water withdrawal amount less than 700 billion m^3, and industrial efficiency to be improved by 20% from 2015 to 2020, and below 40 m^3 from 2015 to 2030). Additionally, sponge cities were set to reduce extensive water use and conserve water by 2030. Production and economic development have to be closely based on local water availability. The *Ministry of Water Resources* and local *Hydrology and Water Resources Investigation Bureaus* would issue access licenses for water withdrawal.

Rather than water market, water right trade, or water pricing with full cost recovery, water neutral development etc., to save water is a priority of policy in China currently for water management. Firstly, water market or water right trade seems unfeasible in China. Water rights are indeed fully considered in the foreign study and overseas water management. Many comprehensive studies, especially those focused on the USA, set water rights for all types of water use, i. e., agriculture, industry, construction, service, household and environment water use, to conduct effective water management. They suggested reducing competition of different types through in accordance with sequence of approval on water right. In the same order, water availability was also assessed and allocated. In other words, they identified the priority of water rights for different water types to assess and allocate water availability (Tae et al. 2011).

However, in China, although the first pilot city of water market has been opened in Kaifeng city, Henan province, in 2015 to alleviate water scarcity, unfortunately, this water market in Kaifeng has been closed afterwards. Specific reasons or enough information could be that water saving issue has not become a priority of governmental attention in ecology and environment field (It is featured and special in China that environmental goals can be probably achieved only with prior attention of government). And the context I mentioned in sections 1.1 and 2.1 above may be also relevant.

There are few research about (cross-) regional water right trade related to Kaifeng city's case. Only Zhang et al. (2017) has some simulation and optimization analysis (in Chinese), choosing water consumption, water use efficiency and transaction priority as control variables. In Zhang et al. (2017) paper, tradable water right of each of 17 cities of Henan province is calculated based on relationship between water supply and demand. In sum, to the best of my knowledge, there is few research or application on water rights in China; a real water market has not been constructed yet.

Secondly, early study on water pricing system and mechanism in China could be from year 2008 (Cai, 2008). Unfortunately, in many places water is regarded as a nearly-free resource and withdrawn unlimitedly (In their daily perception, some people from water-sufficient areas even will not pay for water, including drinking water), and the price has been distorted for many years, i. e., water tariff in China is unreasonable to reflect true value of water resources. Water price is only limitedly effective to change users' decisions, because government's mind is set to maintain a low water price for social security concerns. For example, urban household water use fees are around 0.27 GBP per ton (in Beijing, for example), composed of 0.17 GBP for fresh water and 0.1 GBP for sewage treatment. In small cities, wastewater bills are less, even for manufacturing.

With regard to water pricing with full cost recovery in China, I find this is still under-developing and may be ineffective at this stage: it has only been applied into an urban water reuse study and in a quite small portion (a research by the World Bank, entitled *North China Water Quality Study Program*). Specifically, according to the investigation and estimation, this 'water pricing with full cost recovery' initiative has cost recovery difficulty due to actual production/sales much lower than design capacity, which is because of commonly shortage of users. Given this fact, this 'water pricing with full cost recovery' initiative may be not suitable for China (or too advanced) at the current stage. In sum, water pricing is not sufficient to facilitate water saving. Water use is still extensive, and some water conservancy initiatives or projects are not in full operation. Due to absence of market mechanism, water resources could not be allocated to the most productive users or places.

Thirdly, it is similar for a concept of water neutral development (Van den Abeele et al. 2017), I find this has not been applied in China at this stage. It has been applied in Japan and the USA (specifically, Texas and California). Given this fact, this initiative may be of potential to be suitable for China in the long future, yet it may be too advanced at the current stage.

Since 2005, many studies have evaluated water saving potential in different sectors for China (Liu et al. 2019a; Blanke et al. 2007; Liu et al. 2008) and its regions (Sun et al. 2018; Cai 2008; Zhao et al. 2009). Yet seldom research take into account cost to economy, while targeting to specific sectors and cities for saving water. Jiang (2009) recommended exploration of cost-effective and long-term saving options by considering disruptions caused to economy. In the study of cost and loss evaluation, Chen et al. (2020b) and Zhao et al. (2021) considered three indicators to measure the cost or benefit to economy: number of sectors, GDP of sectors and employment of sectors. Zhang et al. (2017) simulated and found economic benefits, measured by GDP, of 11 cites out of 17 in Henan province would increase under the context of water right trade.

Besides, many studies have focused on agricultural intensification (Tilman et al. 2011; Cai and Rosegrant 2004) in relation to better water management in land use (Lambin and Meyfroidt 2011) and irrigation (Matson et al. 1997). Mitchell and McDonald (2015) conducted theoretical model on cap and trade of water resource to avert shortage. However, due to lack of measured efficiency data as benchmark performance on water withdrawal intensity, there remains a dearth of research especially from an sectoral and industrial perspective (Tillotson et al. 2014), to explore water-saving potential and implication on scarcity alleviation (Liu et al. 2019a) at the city level.

2.4. Research gaps

2.4.1. High-resolution water withdrawal accounting methods and accounts in China

Sectoral methods at the city level are still insufficient, and a sectoral water inventory of China’s cities has scarcely been attempted. There are three possible reasons for this gap: First, current researches and methods on water accounts focused on water quality (Wada et al. 2014b). Most water-related statistics and simulations have concentrated on water pollution and hydrology, with few methods and inventories focusing on water withdrawal. Second, some official statistics, such as those from the Chinese statistical bureaus, do not provide consistent or continuous statistics on water use no matter they are at the nation, province (shire) or city level. Third, the definitions of these statistics have frequently changed in terms of their caliber and period, reducing the possibility of comparison. Compared to developed countries, such as Australia etc. (Vardon et al. 2007; Brandt 2001; Baynes et al. 2010), water accounting in China has already fallen behind (Zhang et al. 2020b). Considering that these data cannot make up a systematic dataset, accurate methods and inventories of water withdrawal at the city level, that can fundamentally illustrate the water use of cities and improve regulations, are still lacking. In sum, city-level and sectoral water withdrawal statistics in China were intermittent. And datasets across all sectors appeared relatively insufficient.

2.4.2. Prefectural water availability and scarcity accounts in China

To the best of my knowledge, an appraisal of cities and their water scarcity status is unavailable. Although nation-wide China is deficient in water (Liu et al. 2008), with a wicked problem between water withdrawal and availability (Shifflett et al. 2015; Liu et al. 2020a), city-level water scarcity has not been fully accounted for Liu et al. (2019b). The criticality ratio has thus far not been applied at the city level (Zeng et al. 2013; Liu et al. 2017; Zhao et al. 2015; Cai et al. 2017), due to data limitations (Wang et al. 2020).

Thus, collation and share of water datasets should be encouraged in China. Developing methods and publishing sectoral water withdrawal and total water availability and scarcity data can be the first step to enrich the existing knowledge base and alleviate water stress (Zhou et al. 2020).

2.4.3. Sectoral water saving potential with targets on specific sectors and cities

Although to save water at the city level has become a priority strategy of regulation and requirement in water field for China, yet how to conduct and realize it among various cities or sectors has not been fixed. Although high water-consumption activities are proposed in a few cities, comparison across the whole cities and economic-sectors is unable to realize. Additionally, there is seldom research taking into account cost to economy, while targeting to specific sectors and cities for saving water. Due to lack of measured efficiency data, there remains a dearth of research especially from an sectoral and industrial perspective (Tillotson et al. 2014), to explore water-saving potential and implication on water stress alleviation (Liu et al. 2019a) and economy disruption at the city level.

Water scarcity is typically exacerbated by unsustainable levels of water withdrawal from economic activities of sectors (Lal 2015; Davis et al. 2015; Hamdy et al. 2003); hence, sectoral water saving should be well placed to alleviate water stress, by improving sectoral water use efficiency, especially by reducing sectoral water withdrawal intensities at a little cost to economy (Jiang 2009; Zwart et al. 2010; Zwart and Bastiaanssen 2004).

Chapter 3 Methods developed for high-resolution water accounts

Collating and estimating sectoral water withdrawal data at the city level is a basic first step toward increasing water conservation. In this chapter, I propose a general methodology for establishing a water inventory for all economic-social-environmental sectors in prefectural cities in China. I disaggregate agriculture, industry, construction, services, household and environment into 65 subsectors.

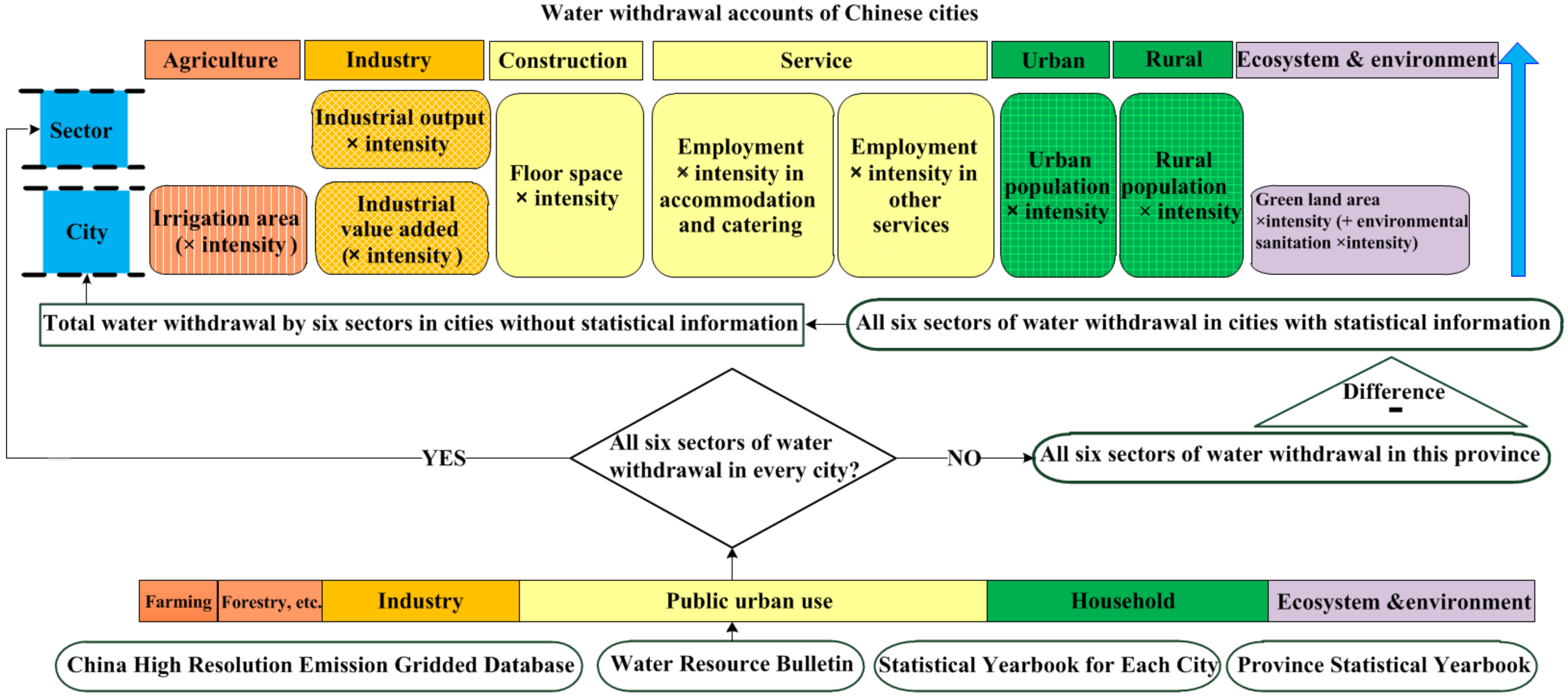
3.1. Scope of total and sectoral water withdrawal accounts

In the IPCC (Intergovernmental Panel on Climate Change) administrative and territorial scope (IPCC 2006), scope 1 was adopted for city water withdrawal. Scope 1 water withdrawal referred to anthropogenic water withdrawal '*taking place within national (including administered) territories and offshore areas* (pageoverview.5)'. In other words, scope 1 accounted all types of water withdrawal within a city boundary: farming, forestry, animal husbandry, fisheries, industry, construction, service, household, and ecosystem and environment preservation. There were 65 sectors in total, as listed in Table 1 of Appendix.

Herein, I prioritize the city level based on two considerations: 1) The city is the basic unit for water circulation between the economy and the environment and for evaluating water regulation policies (Li et al. 2019b). 2) Compared with the provincial and national dimensions, city-level water use provides more disaggregated information. It is worth mentioning that the definition of China's prefectural cities here spanned both rural and urban geographies, which was distinguished from built-up districts that indicated only a part of urban areas.

The framework for the water inventory at the city level is illustrated in Figure 3. There are six sectors of water withdrawal illustrated by six different colors (i. e., dark red for farming; light red for forestry, animal husbandry, fisheries; orange for industry; yellow for construction and services; green for urban and rural household; and purple for ecology and environment water withdrawal). Water withdrawal in this study is the water allocated to final users, including the water lost during delivery, and it mainly includes surface water and groundwater. According to the current statistical definitions of the water resources bulletins at the city level, water withdrawal can be generally classified into six sectors as follows (The Ministry of Water Resources 2019):

First, the **water used in farming** is the water withdrawal by wheat cultivation, maize cultivation, vegetables & fruits cultivation, fiber and bean etc. cultivation, and rice cultivation for irrigation of paddy fields, irrigated croplands, and vegetable plots etc.. Second, the **water used in forestry, animal husbandry, and fisheries** represents irrigation for forests and fruit trees, grassland preservation, fishpond maintenance, and cattle husbandry. Third, for **industrial water withdrawal**, according to China Water Resources Bulletin (The Ministry of Water Resources 2019), water withdrawal is a newly withdrawn water amount allocated to end users. This variable may depict pressure on available water resources from local economic activities more accurately since it excludes reused water (Zhang et al. 2020b). Industrial water withdrawal covers water use of coal-fired and nuclear power plants, but excluded intra-river water use, such as hydro-power generation. It also includes tap water applications of public water supply, water pump and self-well etc. general industrial applications for food production, chemical manufacturing etc.. Fourth, the **public water withdrawal in urban areas** is defined as the sum of the water withdrawal in construction and all service sectors. This definition of water withdrawal is a statistical feature that is different from other resource and economic statistics. Fifth, the **water withdrawal by household** consists of the water withdrawal by urban and rural residents in households. Finally, the **water withdrawal for ecosystem and environment preservation** includes grassland irrigation, deep well injection, environmental sanitation and improvements, and the supplementation of rivers, lakes, and marshes. Water for environmental sanitation means water used to help keep the environment clean and beautiful. Environmental sanitation area is the area cleaned, including roads, squares and parks etc..



Note: The circled sources at the bottom indicate the primary input for estimation.

Figure 3 An accounting framework for sectoral water withdrawal inventory at the city level

3.2. A general framework for high-resolution accounts for water withdrawal

In Figure 3, each of the six sectors of water withdrawal is displayed in a unique color (i. e., dark red for farming; light red for forestry, animal husbandry, fisheries; orange for industry; yellow for construction and services; green for urban and rural household; and purple for ecology and environment water withdrawal) and organized from bottom to top vertically. Based on water balances between prefectures and provinces (Zhou et al. 2020; Vörösmarty et al. 2000; Liang et al. 1994), there were three specific procedures (please see detail in section 3.2.3.). I realized the partition firstly at the city level and then at the sectoral level.

3.2.1. Featured selection of 22 driving forces

This framework features in selection of 22 driving forces in total. I connected each size indicator with its unique water-withdrawal efficiency. A series of socio-economic driving forces were highly correlated to water withdrawal of individual type (Figure 4). These indicators were selected with their unique efficiency. For example, in service, I used the number of sectoral employees rather than value added (Zhou et al. 2020), considering it is more reasonable to assume a positive correlation between water use and the number of employees rather than value added of economy in the service sector. For household, because urban residents usually use more water per resident than rural residents, how much water a city uses is determined by not only its absolute population but also its urbanization structure. Thus, it is necessary to combine the population with its respective water withdrawal per resident.

Table 3 The 22 driving forces and their source

<table>
<tr><th colspan="2">Type</th><th>Driving force</th><th></th><th>Source</th></tr>
<tr><td colspan="2" rowspan="2">Agriculture</td><td>Irrigation areas</td><td>○</td><td rowspan="22">○ Province statistical yearbook

Δ City statistical yearbook

○/Δ Province or city statistical yearbook or internet search

√ Water resources bulletins

※ China High Resolution Emission Gridded Database

X Bulletin of the First Water Resources Census (the 2nd Water Census of Shanghai)

∪ China City Statistical Yearbook</td></tr>
<tr><td>Irrigation water withdrawal per mu for farmland</td><td>√</td></tr>
<tr><td colspan="2" rowspan="4">Industry</td><td>Total industrial value added</td><td>○/Δ</td></tr>
<tr><td>Water withdrawal per industrial value added</td><td>√</td></tr>
<tr><td>Sectoral industrial output</td><td>Δ</td></tr>
<tr><td>Disaggregated water withdrawal intensity of each sector</td><td>※</td></tr>
<tr><td colspan="2" rowspan="2">Construction</td><td>Floor space of housing</td><td>○</td></tr>
<tr><td>Water withdrawal per floor space of housing</td><td>X</td></tr>
<tr><td rowspan="4">Services</td><td rowspan="2">Accommodation & catering</td><td>Number of employees in accommodation & catering</td><td>∪</td></tr>
<tr><td>Water withdrawal per employee in accommodation & catering</td><td>X</td></tr>
<tr><td rowspan="2">Other services</td><td>Number of employees</td><td>∪</td></tr>
<tr><td>Water withdrawal per employee in other services</td><td>X</td></tr>
<tr><td rowspan="4">Household</td><td rowspan="2">Rural</td><td>Rural population (permanent residents)</td><td>○</td></tr>
<tr><td>Household water withdrawal per capita in rural areas</td><td>○/Δ</td></tr>
<tr><td rowspan="2">Urban</td><td>Urban population (permanent residents)</td><td>○</td></tr>
<tr><td>Household water withdrawal per capita in urban areas</td><td>○/Δ</td></tr>
<tr><td colspan="2" rowspan="6">Environment & ecology</td><td>Green land areas</td><td>∪</td></tr>
<tr><td>Irrigation volume per green land area in urban areas</td><td>X</td></tr>
<tr><td>Environmental sanitation areas</td><td>Δ</td></tr>
<tr><td>Water withdrawal per unit</td><td>X</td></tr>
<tr><td>Livestock (for year 2013 and before)</td><td>○</td></tr>
<tr><td>Water withdrawal per cattle (for year 2013 and before)</td><td>√</td></tr>
</table>

A total of 22 variables were taken into account. This is illustrated in Table 3. For each city, changes in the intensity and variability of each parameter were considered. In specific calibration, I tuned the water withdrawal according to local statistics, such as the gross water withdrawal in each of the sectors, which I think gives a relatively accurate reflection of local water status. Even in Case 2.2, where not all data were available, I considered the differences between cities, and used intensities from an economically or demographically similar region to estimate cities at a similar stage because I think that the local information is valuable and unique (He et al. 2011a, 2011b).

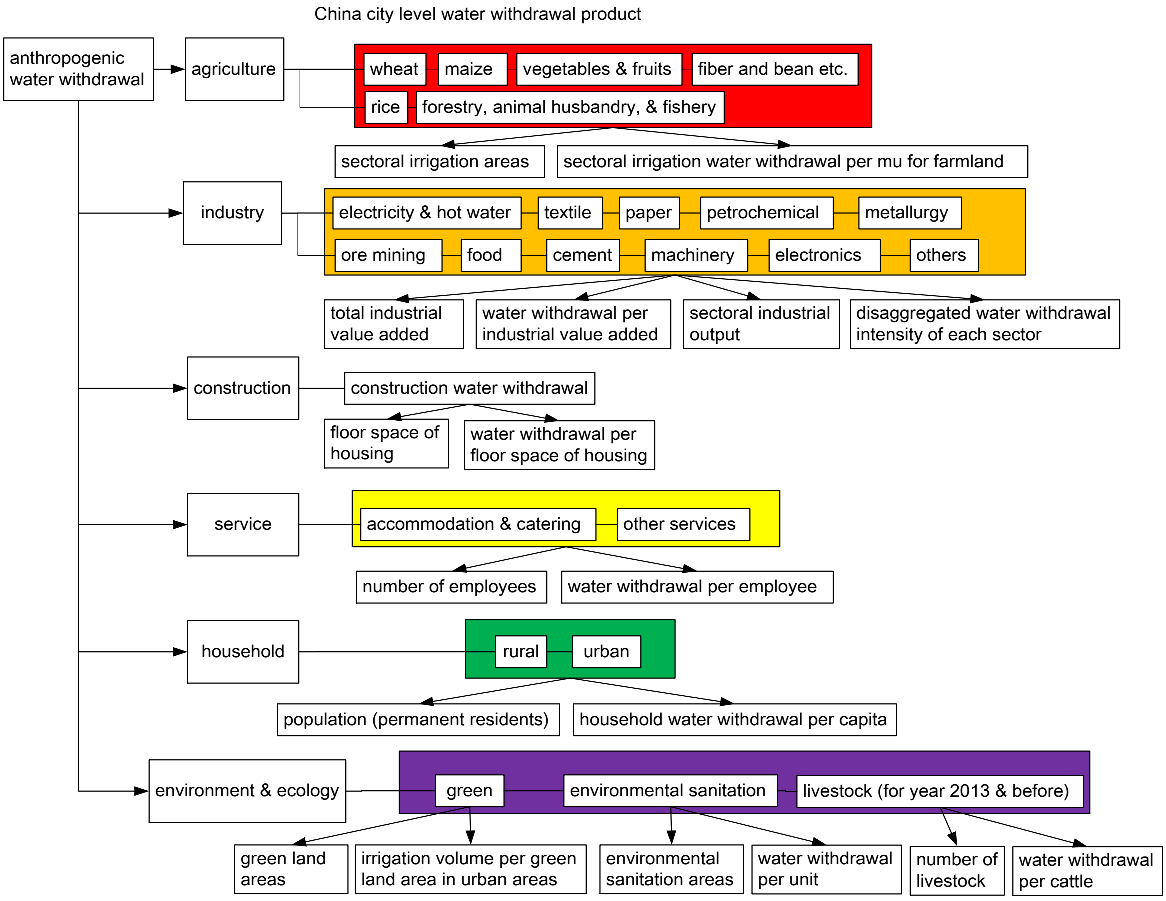


Figure 4 Featured selection of 22 driving forces for water withdrawal

Note: this is in furtherance of previous Figure 3.

3.2.2. Data sources

For 343 prefectures and 41[9] industrial sectors (appendix Table 12), individual

[9] This is for industry only.

intensities (water withdrawal per industrial output) were derived from the China High Resolution Emission Gridded Dataset (Cai et al. 2018). A point-sourced survey of 2015 covered 162,000 enterprises in total (approximately 42% of all above designated-size enterprises in China; above designated-size enterprise referred to those with annual business revenue over 20 million yuan after 2011 (Anon 2012)). Through the survey, I obtained water withdrawal efficiency, as benchmark performance. Concretely, the intensities were calculated as the sectoral water withdrawals divided by the industrial output of sample enterprises.

Total water withdrawal of six types, irrigation water withdrawal per mu for farmland (1 mu≈667 m^2, and it is commonly used by water resources bulletin in provision), industrial water withdrawal per value added, and water availability were sourced from water resources bulletins at the province and city levels (Li et al. 2020), issued by the *Ministry of Water Resources* and local *Hydrology and Water Resources Investigation Bureaus*[10]. Due to data unavailability, I used some data in 2013. Specifically, total irrigation water withdrawal of farming of 156 cities, and sectoral irrigated area and sectoral water withdrawal per irrigated area data (by 5 main crops) in 2013 of 343 prefectures were obtained from Zhou et al. (2020). The 'irrigation utilization-coefficient in farmland' measure was represented by agricultural water withdrawal per irrigated area for calculation in the following Chapters 5 and 6, due to data availability. At the city level, only less than one fifth of 343 prefectures have the 'irrigation

[10] The water withdrawal coefficients are from estimations of water resources bulletin. End use metering is preferable to use. In case metering or monitor is only limitedly applied or used, due to incomplete installation of metering or other gauging facilities, estimations based on quota have been combined with metering in some cities.

utilization-coefficient in farmland' data available.

Water withdrawal per floor space of housing completed, water withdrawal per capita in representative accommodation and catering, water withdrawal per capita in other services, irrigation water withdrawal per green land in urban areas, and water withdrawal per environment and sanitation area, were sourced from the bulletin of 1st water resources census (2nd water census of Shanghai) in 2011. Irrigation area, floor space of housing, rural and urban population (permanent resident), were obtained from provincial statistical yearbooks. Sectoral industrial output, and environmental sanitation area were taken from statistical yearbooks for each city. Total industrial value added, and household water withdrawal per capita in both rural and urban areas were from province or city statistical yearbooks. The number of employees in accommodation and catering and other services, and green land area were from China City Statistical Yearbook.

In water resources bulletins, I found there were 187 cities out of 343 cities, with irrigation water withdrawal statistics of farming separated with forestry, animal husbandry, and fishery (16 provinces out of 31). For those without these statistics, I used ratio of farming irrigation to the entire agriculture from nearby cities (or within the same province) instead. This ratio was 0.925 for cities from Hunan, Jiangxi, Chongqing, and Guizhou provinces (municipalities); 0.88 for cities from Beijing, Tianjin, Hebei, Liaoning, and Shandong provinces (municipalities); and 0.875 for cities from Shanghai, Jiangsu, and Zhejiang provinces (municipalities). I had no data for Hong Kong, Macao and Taiwan due to limited statistic availability.

There are 65 sectors in total. As illustrated by the shaded sectors in appendix, 1-5 are crop cultivation, 6 is forestry, animal husbandry, and fishery, 7-13 are associated with mining and processing, 14-44 are manufacturing, 45-47 are production and supply of electricity, gas and hot water, 48 is construction, 49-62 are services, 63 is urban household, 64 is rural household and 65 is ecosystem and environment. These were selected based on the National Accounting System and are widely used as industrial classifications, i. e., classification for national economic activities, released by the National Administration for Quality Supervision, Inspection and Quarantine (AQSIQ-PRC 2016) (Li et al. 2019b)[11].

In this way I constructed China's city-level water withdrawal inventories with 65 sectors and 343 cities, total water withdrawal, water availability and criticality ratio. In 343 cities, only 272 cities' (88% of China's population) data were available for industrial sectoral-accounting, and 343 were further accounted for total water withdrawal, availability and water scarcity status.

The datasets 'City-level water withdrawal, availability and scarcity accounts of China in 2015' would be made public under Figshare. A total of 35 data records (sectoral water withdrawal and total water withdrawal, water availability and criticality ratio

[11] Main difference for water accounting of this classification from the *International Standard Industrial Classification* lies in the farming and livestock under agriculture. Briefly speaking, classification of this study has much less disaggregated sub-sectors under farming and livestock. Specifically for blue water accounting, the *International Standard Industrial Classification* has 13 disaggregated sub-sectors (by 13 crops) under farming, and 12 disaggregated sub-sectors under livestock (Stadler et al. 2018); while this study has 5 crops and 1 livestock (yet it should be one of the most updated in China). These disaggregated sub-sectors are accounted for individual blue water consumption by simulation, while this study is for blue water withdrawal, due to data availability stated in Chapter 2.

inventories) were assembled in the datasets. Among these, 1) 34 are city-level sectoral water withdrawal inventory (in the sequence of 34 province-level administrative units, 2015); 2) one is city-level total water withdrawal, water availability and criticality ratio inventory.

3.2.3. Accounting method

In Figure 3, each of the six sectors of water withdrawal is displayed in a unique color (i. e., dark red for farming; light red for forestry, animal husbandry, fisheries; orange for industry; yellow for construction and services; green for urban and rural household; and purple for ecology and environment water withdrawal) and organized from bottom to top vertically. Based on water balances between prefectures and provinces (Zhou et al. 2020; Vörösmarty et al. 2000; Liang et al. 1994), there were three specific procedures. I realized the partition firstly at the city level **B)** and then at the sectoral level **C)** under individual city. Module B is for city partition for 343 prefectures; and C is for sectoral partition for 65 sectors under individual city of B. Three procedures are as follows: **A)** I looked for the water withdrawal for cities in a province by the six sectors from the provincial water resources bulletin. I divided the provinces into two cases based on the available data.

Case 1) If the water resources bulletin for this province provided water withdrawal for the six sectors for every administrative city, these data were compiled for later use (in the sectoral module). I allocated water withdrawal into each disaggregated subsector in Table 12 of the appendix for each city, including agriculture, industry, construction, services, urban households, rural households, and environmental water withdrawal.

Case 2) If the water resources bulletin did not provide water withdrawal for the six sectors for all administrative cities, I then turned to the water resources bulletin for each city to find water withdrawal for the six sectors for each city. For those cities that did not have these figures in their own water resources bulletin, for each of the six sectors, I calculated the difference between the provincial magnitude and the sum of the water withdrawals for all cities that did have statistics in their city water resources bulletins. Thus, I obtained the sum for each of the six sectors for all cities where water withdrawal for the six sectors was not included in their water resources bulletin. Overall speaking, cities from Jiangsu, Zhejiang, Guangdong, Anhui, Hainan, Heilongjiang, Tibet, and Jilin were categorized as *Case 2* in 2015. Remaining cities were in *Case 1*. Approximately one fifth of 343 cities did not collect or develop water data statistics. For data of the other four fifths of cities, there were only total numbers of six types provided.

B) Here, I allocated the sum of each sector for those cities without statistics; each sector had two multipliers, which are illustrated by the same color in Figure 3 (i. e., dark red for farming; light red for forestry, animal husbandry, fisheries; orange for industry; yellow for construction and services; green for urban and rural household; and purple for ecology and environment water withdrawal), that were selected as the driving forces of water use according to the current literature (Fan et al. 2019c). The logic behind this process is simple: I use a variable to multiply its water withdrawal intensity in the allocation. If the intensity was missing, I instead used these indicators to calculate the proportions to disaggregate the water withdrawal (see the detailed uncertainty analysis discussion below).

I used (1) the irrigation water withdrawal per mu of farmland and the irrigation area to determine agricultural water use according to the data availability below. (mu is Chinese acre, 1 mu≈667 m^2).

Case 2.1) For cities with data for both the irrigation water withdrawal per mu (*Intensity*) and the irrigation area (*Irriareas*), I immediately obtain

$$Water_{i,1-6} = Irriareas_{i,1} * Intensity_{i,1-6} \tag{3}$$

where $Water_{i,1-6}$ is irrigation water withdrawal in city *i* for agriculture, $Irriareas_{i,1}$ is irrigation area of city *i* for agriculture (represented by farming), and $Intensity_{i,1-6}$ is irrigation water withdrawal per mu of city *i*. 1-6 denote the first 6 of 65 economic activities. Irrigation area was from provincial statistical yearbooks.

As there is little uncertainty, this case is considered an advancement of previous studies such as Vardon et al. (2007), which used only the irrigation area by assuming that the irrigation water withdrawal per mu was equal among regions.

Case 2.2) If a city did not provide the irrigation water withdrawal per mu, I used the irrigation area instead, and I acknowledge that this does result in uncertainty (see detailed discussion below). In addition, because irrigation areas are close to the sown areas by definition, the sown areas could also be used in case that some cities did not provide the irrigation areas.

$$Water_{i,1-6} = Irriareas_{i,1-6} / \sum_{i=1}^{j} Irriareas_{i,1} * Water_{j,1-6} \tag{4}$$

where j denotes the number of cities that did not provide figures in their own water resources bulletins, and $Water_{j,1-6}$ represents the sum of agricultural water withdrawal for those cities without statistical information. Irrigation water withdrawal per mu for farmland (1 mu≈667 m^2) was sourced from water resources bulletins at the province and city levels (Li et al. 2020), issued by the *Ministry of Water Resources* and local *Hydrology and Water Resources Investigation Bureaus*.

(2) Total industrial value added and water withdrawal per unit (*Intensity*) were used for industrial water withdrawal. Similar to *Case 2.1*, for cities with both indicators, I obtained

$$Water_{i,7-47} = Valueadded_{i,7-47} * Intensity_{i,7-47} \quad (5)$$

where $Water_{i,7-47}$ is industrial water withdrawal in city i, $Valueadded_{i,7-47}$ is industrial value added of city i, and $Intensity_{i,7-47}$ is industrial water withdrawal per value added of city i. 7-47 denote the 7^{th} to 47^{th} of 65 economic activities. Industrial water withdrawal per value added was sourced from water resources bulletins at the province and city levels (Li et al. 2020), issued by the *Ministry of Water Resources* and local *Hydrology and Water Resources Investigation Bureaus*. Total industrial value added was from province or city statistical yearbooks.

In this case, there is also little uncertainty, which is a step beyond Guan et al. (2014), which assumed that industrial water withdrawal per value added was identical among regions. I regarded those cities with only value-added data as *Case 2.2*.

(3) I utilized the floor space of housing (*Flospac*) and the water withdrawal per unit (*Intensity*) to estimate water withdrawal for construction. For water withdrawal for accommodation and catering sector, which is usually the largest water user in the service sector, I assumed a positive correlation between water use and the number of employees and then used employment and water withdrawal per employee (*Intensity*).

$$Water'_{i,48} = Flospac_{i,48} * Intensity_{i,48} \tag{6}$$

$$Water'_{i,51} = Employment_{i,51} * Intensity_{i,51} \tag{7}$$

$$Water'_{i,k} = Employment_{i,k} * Intensity_{i,k}, k \in [49,50] \cup [52,62] \tag{8}$$

where $Water'_{i,48}$ is original water withdrawal in city *i* for construction, $Flospac_{i,48}$ is floor space area of housing of city *i* for construction (represented by completed floor space), and $Intensity_{i,48}$ is water withdrawal per floor space area of housing of city *i*. 48 denotes the 48th of 65 economic activities. $Water'_{i,51}$ is original water withdrawal in city *i* for accommodation and catering sector, $Employment_{i,51}$ is number of employees of city *i* for accommodation and catering sector (key water user), and $Intensity_{i,51}$ is water withdrawal per employee of city *i*. 51 denotes the 51st of 65 economic activities. Similarly, $Water'_{i,k}$ is original water withdrawal in city *i* for the other services other than accommodation and catering sector (ordinary water users), $Employment_{i,k}$ is number of employees of city *i* for the other services other than accommodation and catering sector, and $Intensity_{i,k}$ is water withdrawal per employee of city *i*. 49-50, and 52-62 denote the corresponding economic activities. Water withdrawal per floor space of housing completed, water withdrawal per capita in representative accommodation and catering, water withdrawal per capita in other services, were from the bulletin of 1st water resources census (2nd water census of Shanghai) in 2011. Floor space of housing was from provincial statistical yearbooks. The number of employees in accommodation and catering and other services were from China City Statistical Yearbook.

(4) I used the rural population (*Popul*, permanent residents) and household water withdrawal per resident in rural areas (*Intensity*) to estimate rural household water withdrawal. The estimation for urban household water withdrawal was quite similar, that is,

$$Water'_{i,k} = Popul_{i,k} * Intensity_{i,k} \tag{9}$$

$$W_{i,k} = Water'_{i,k} / \sum_{k=63}^{64} Water'_{i,k}, k \in [63,64] \tag{10}$$

where $Water'_{i,k}$ is original water withdrawal in city *i* for household, $Popul_{i,k}$ is rural (or urban) population of city *i* (represented by number of permanent residents), and $Intensity_{i,k}$ is household water withdrawal per resident in rural (or urban) areas of city i. $W_{i,k}$ is the proportion of rural (or urban) household water withdrawal in total household water withdrawal. 63-64 denote the 63rd and 64th of 65 economic activities. Rural and urban population (permanent resident) were from provincial statistical yearbooks. Household water withdrawal per capita in both rural and urban areas were from province or city statistical yearbooks[12].

(5) I used the area of green land, irrigation volume per green land area in urban areas (*Intensity* equals 0.0782 cubic meters), environmental sanitation areas (*Sanitarea*), and the water withdrawal per unit (*Intensity'* equals 0.0265 cubic meters) to estimate ecosystem and environment water withdrawal, that is,

$$W\text{ater}_{i,65} = Greenarea_{i,65} * Intensity_{i,65} + Sanitarea_{i,65} * Intensity'_{i,65} \quad (11)$$

where $W\text{ater}_{i,65}$ is water withdrawal in city *i* for ecosystem and environment, $Greenarea_{i,65}$ is area of green land of city *i* (represented by urban green land areas at this stage), and $Intensity_{i,65}$ is irrigation volume per green land area in urban areas of city *i*. $Sanitarea_{i,65}$ is environmental sanitation areas of city *i*, and $Intensity'_{i,65}$ is water withdrawal per unit of city *i*. 65 denotes the 65th of 65 economic activities. Irrigation water withdrawal per green land in urban areas, and water withdrawal per environment and sanitation area, were from the bulletin of 1st water resources census (2nd water census of Shanghai) in 2011. Environmental sanitation area was taken from statistical yearbooks for each city. Green land area was from China City Statistical Yearbook.

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[12] Total household size effect was considered and reflected because different household sizes (represented by a total population of a city, from rural and urban aspect respectively; that is, I compare total rural population and intensity in a city No. 1# and total rural population and intensity in a city No. 2#, etc.) have its own and unique water use per capita. I would continue another study focusing on this household size and per capita water use, and a scale-economy related study entitled *Environmental Kuznets curve of water use among Chinese cities* to further check whether data support a decline relationship between per capita use and increasing household size, from an empirical and robust perspective.

C) is in the sectoral module. Firstly, for irrigation water withdrawal of farming and its subdivisions in 2015, I first compiled total water withdrawal of farming from water resources bulletin (Li et al. 2020). Then I used the data in 2013 of Zhou et al. (2020) and calculated proportions of irrigation for 5 crop cultivation sectors in 343 prefectures. At last, sectoral water withdrawal per irrigated area (by crop) was calculated based on sectoral irrigated area data in 2013 from Zhou et al. (2020).

Secondly, for industrial water withdrawal, I utilized the disaggregated water withdrawal intensity and sectoral industrial output of each sector to divide the total industrial water withdrawal in each city (*WaterIndus*), that is,

$$W_{i,k} = Intensity_{i,k} \times Output_{i,k} / \sum_{k=7}^{47}(Intensity_{i,k} \times Output_{i,k}) \quad (12)$$

$$Water_{i,k} = W_{i,k} \times WaterIndus_i, k \in [7,47] \quad (13)$$

where $W_{i,k}$ is the proportion of sectoral industry water withdrawal in total industry water withdrawal. $Intensity_{i,k}$ is the disaggregated water withdrawal intensity. $Output_{i,k}$ is sectoral industrial output of each sector. $Water_{i,k}$ is divided and sectoral industry water withdrawal in city i. $WaterIndus_i$ is total industrial water withdrawal in city i. 7-47 denote the 7^{th}-47^{th} of 65 economic activities. For 343 prefectures and 41 industrial sectors (appendix Table 12), individual intensities (water withdrawal per industrial output) were derived from the China High Resolution Emission Gridded Dataset (Cai et al. 2018). A point-sourced survey of 2015 covered 162,000 enterprises in total (approximately 42% of all above designated-size enterprises in China; above designated-size enterprise referred to those with annual business revenue over 20 million yuan after 2011 (Anon 2012)). Through the survey, I obtained water withdrawal efficiency as benchmark performance. Concretely, the intensities were calculated as the sectoral water withdrawals divided by the industrial output of sample enterprises. Sectoral industrial output was taken from statistical yearbooks for each city.

Similarly, I used the proportions of water withdrawals (original magnitude indicated by *Water'*) in construction, accommodation and catering and other services to separate urban and public water withdrawal. This procedure is more plausible than that used in Guan et al. (2014), which assumed that the water intensities of construction and all services were the same.

$$Water_{i,k} = Water'_{i,k} / \sum_{k=48}^{62} Water'_{i,k} * (Water_{i,UrbanPublic}), k \in [48,62] \quad (14)$$

$$Water_{i,k} = W_{i,k} \times Waterhousehold_i, k \in [63,64] \quad (15)$$

In Eq. (14), $Water_{i,k}$ disaggregated and sectoral water withdrawal for construction and services in city *i*. $Water'_{i,k}$ is the original and sectoral water withdrawal for construction and services in city *i*. $Water_{i,UrbanPublic}$ is total urban and public water withdrawal in city *i*. 48-62 denote the 48^{th}-62^{nd} of 65 economic activities.

In Eq. (15), $W_{i,k}$ is the proportion of rural (or urban) household water withdrawal in total household water withdrawal. It is used to partition total household water withdrawal into rural and urban household sectors on an occasion that I could only get a total number of household water withdrawal. $Water_{i,k}$ is disaggregated and sectoral water withdrawal for rural or urban household in city *i*. $Waterhousehold_i$ is total household water withdrawal in city *i*. 63-64 denote the 63rd-64th of 65 economic activities.

For example, industrial water withdrawal was accounted through procedures **<u>A</u>)**, **<u>B</u>)** and **<u>C</u>)** and *Case 1)* and *Case 2)* in a row: A) I compiled industrial water withdrawal for cities in a province from provincial water resources bulletins. There were two cases to consider based on data availability: *Case 1)* If water resources bulletin for a province provided industrial water withdrawal for every administrative city, these data were compiled for later use in sectoral partition. I allocated water withdrawal into each disaggregated sector in appendix Table 12 for each city. *Case 2)* If water resources bulletin did not provide water withdrawal for industrial type for all administrative cities, I then collected industrial water withdrawal for each city in their corresponding water resources bulletins. For those cities that did not have these data in their respective bulletins, I calculated difference between provincial water withdrawal and the sum of water withdrawal for all cities that did have statistics in their city-level water resources bulletins, based on water mass balance. In this way, I obtained a sum for all cities for which water withdrawal of industrial type was not included in their water resources bulletins.

Then in B) I allocated the sum of industrial type for those cities without statistics, based on two multipliers as driving forces of water withdrawal. I used total industrial value added ($Valueadded_i$, size indicator) multiplying water withdrawal per value added ($Intensity_i$) in the partition. According to data availability, for cities having data for both water withdrawal per value added and total industrial value added, I immediately obtained Eq. (16) and Eq. (17), where *i* stood for a city without statistics in this province and *n* represented total number of cities without statistics. This case was considered as a step further beyond previous studies such as Guan et al. (2014), which assumed that industrial water withdrawal per value added was identical among regions. In case that the intensity was missing, I instead used total industrial value added to calculate proportions to disaggregate water withdrawal, and I acknowledged that this did result in uncertainty. In C) I used disaggregated industrial output (Dang et al. 1994) and water withdrawal per output of each sector ($Intensity_{i,k}$) to partition total industrial water withdrawal of each city (*WaterIndus*), due to a lack of sectoral value added data. That is in Eq. (18) and Eq. (19), where k represented a sector of city i. In case disaggregated industrial outputs were missing, I used disaggregated industrial product-sales instead, because they were close to outputs.

$$W_i = Valueadded_i * Intensity_i / \sum_{i=1}^{n}(Intensity_i \times Valueadded_i) \quad (16)$$

$$WaterIndus_i = W_i \times SUM_{n\ cities} \quad (17)$$

$$W_{i,k} = Intensity_{i,k} \times Output_{i,k} / \sum_{k=7}^{47}(Intensity_{i,k} \times Output_{i,k}) \quad (18)$$

$$Water_{i,k} = W_{i,k} \times WaterIndus_i, k \in [7,47] \quad (19)$$

3.3. Uncertainties and comparisons

3.3.1. Sensitivity analysis

For method validation I refer to Turner et al. (2010) and follow procedures in Shan et al. (2016) (Shan et al. 2016). Overall speaking, for case 2 on estimations for cities without water withdrawal statistics, water withdrawal efficiency is an essential part of the inventories' uncertainties. I conducted sensitivity analyses through replacing these efficiency data with regional efficiency. It showed differences between replaced total industrial water withdrawal and the original estimations ranged from -13.5% in Xuzhou, Lianyungang, and Huai'an, to 9.5% in Nantong, Zhenjiang and Taizhou. And average difference in absolute value was at 7.3%. This result indicated relatively low difference, and validated the method in case 2 as a credible estimation of industrial water withdrawal. Similarly, difference ranges were shown 9.0% for agriculture water withdrawal, 8.0% for service water withdrawal, compared to estimations with regional intensities. I omitted sensitivity tests for environment and ecology water withdrawal due to a lack of comparable data on water withdrawal per sanitary area (Xu et al. 2021). There was little uncertainty for case 1.

Specifically, I estimated the sensitivity of water withdrawal by agriculture, industry, and services for cities in *Case 2.2* by replacing the specific intensity value with regional, provincial or national magnitudes based on data availability. I take the cities of Anhui, Jiangsu, and Zhejiang as examples because their water resources bulletin did not provide water withdrawal for the six types for some of their cities.

For agricultural water withdrawal in Case 2.2, one assumption was applied for cities without statistical information: If there was no available irrigation water withdrawal per mu for farmland, the water withdrawal intensity for the agriculture sector would be the same. I conducted a sensitivity analysis by replacing the intensity with the regional or provincial values, the results of which are shown below:

Table 4 Sensitivity analysis of agricultural water withdrawal

City	Original agricultural water withdrawal (10^6 m^3)	Irrigation area (10^3 hectare)	Irrigation water withdrawal (m^3) /mu for farmland	Replaced agricultural withdrawal for sensitivity test (10^6 m^3)	Percentage difference (%)[13]
Hefei	1503	458	282	1295	13.9
Bengbu	778	237	282	670	13.9
Huaibei	468	143	282	403	13.9
Tongling	268	82	282	231	13.9
Huangshan	168	51	282	145	13.9
Suzhou	1384	422	282	1192	13.9
Xuancheng	658	201	282	567	13.9
Wuxi	610	173	461	711	-14.3
Xuzhou	4086	1161	389	4024	1.6
Changzhou	756	215	461	882	-14.3
Nantong	2942	836	389	2898	1.5
Lianyungang	2231	634	389	2197	1.6
Huai'an	2801	796	389	2758	1.6
Zhenjiang	831	236	389	818	1.5
Taizhou	2046	581	389	2015	1.5

Note: the percentage difference is calculated as (column2- column5)/ column2*100%.

Although the largest differences between *Agricultural water withdrawal'* (estimated with the replaced agricultural water withdrawal intensity) and the original estimation appeared in Wuxi and Changzhou (-14.3%) in Table 4, the average difference of the absolute value was 9.0%. This result indicates that there are no substantial differences, and the method in Case 2.2 provides a credible estimation of agricultural water

[13] + and - are determined by whether actual intensity of selected sample is higher than the provincial average or not in their respective sector. Table 4 is for agriculture and table 5 is for industry. Table 4 and table 5 are somehow separated or independent from each other.

withdrawal.

Table 5 Sensitivity analysis of industrial water withdrawal

City	Original industrial water withdrawal (10^6 m^3)	Industrial value added (10^9 yuan)	Industrial water withdrawal (m^3)/ 10^3-yuan value added	Replaced industrial withdrawal for sensitivity test (10^6 m^3)	Percentage difference (%)
Hefei	964	226	4.5	1011	-4.8
Bengbu	291	68	4.5	305	-4.8
Huaibei	214	50	4.5	225	-4.8
Tongling	185	43	4.5	194	-4.8
Huangshan	54	13	4.5	57	-4.8
Suzhou	157	37	4.5	165	-4.8
Xuancheng	176	41	4.5	184	-4.8
Wuxi	520	295	1.5	502	3.7
Xuzhou	477	271	1.8	552	-13.5
Changzhou	461	262	1.5	444	3.7
Nantong	511	290	1.4	467	9.5
Lianyungang	204	116	1.8	236	-13.5
Huai'an	261	148	1.8	302	-13.5
Zhenjiang	358	203	1.4	327	9.5
Taizhou	434	247	1.4	397	9.5

Note: For cities in Anhui, I could obtain only the industrial value added for the above-designated-sized enterprises. The percentage difference is calculated as (column2-column5)/ column2*100%.

For the industrial water withdrawal estimation, although the largest differences between *Industrial water withdrawal'* (estimated with the replaced water withdrawal intensity) and the original estimation appeared in Xuzhou, Lianyungang, and Huai'an (-13.5%) in Table 5, the average difference in the absolute value was 7.3%. This result indicates that there is relatively low sensitivity, and the method in Case 2.2 provides a credible estimation of industrial water withdrawal. Moreover, the cities were the same as those selected for the validation of agricultural water withdrawal, which also supports the robustness of the method.

Similarly, for services, I assumed that the water withdrawal per employee would be equal within a city (for cities with statistical information) or among cities (for those without). I estimated the uncertainty of other services using water withdrawal per employee at the national level from the cities with statistical information. The list of cities used is provided in Appendix II. I observed that the average difference was 8.0%. This result indicates that there are no large differences, and the method in Case 2.2 provides an accurate and credible method for estimating service water withdrawal. In fact, similar proportions were also used in the estimations of the China Institute of Water Resources and Hydropower Research (Xie et al. 2015; Gan et al. 2013; Zhang et al. 2013).

For construction (and household), I assumed that the water withdrawal per floor space of housing completed (and resident) would be equal within a city (for cities with statistical information) or among cities (for those without). I estimated the uncertainty of construction (and household), using water withdrawal per floor space of housing completed (and resident) at the national level from the cities with statistical information. The list of cities used is provided in Appendix II. I observed that the average difference was 9.8% (and 9.4%). This result indicates that there are no large differences, and the method in Case 2.2 provides an accurate and credible method for estimating construction (and household) water withdrawal(s).

Finally, given that China did not officially report statistics on environmental sanitation areas at this stage, I omitted the validation of environmental water withdrawal. Nevertheless, this will be possible when such data are available, considering that many cities are beginning to explore how to estimate their environmental sanitation areas.

Notably for regionalization of water withdrawal in each city, variability of intensity is considered. China’s cities showcase distinctive characteristics in terms of age, size, coverage, population, resource endowment and industrial drivers, and this diversity indicates different economic development levels. Hence, I tuned water withdrawal based on local statistics, such as gross water withdrawal in each type, for calibration. This calibration reflects local water status accurately. Even in Case 2 where not all data are available, differences between cities are considered and intensities of economically and demographically similar regions are used to estimate for cities at a similar stage (Lv et al. 2017). Thus the datasets may be more advanced than those in Vardon et al. (2007), (Karimi et al. 2013) or Guan et al. (2014), which assumed agriculture-, industry-, construction- and service-water withdrawal intensities were identical for every city and even transferred information and data of rich cities to serve for poor cities. For example, because to implement its WA+ framework does not necessarily require local-measured or representative indicators or efficiency data, Karimi et al. (2013)’ results may suffer from considerable biases.

Besides, estimating city-level water withdrawal by deducing or scaling down the numbers from the administrating-province statistics was not feasible because the sectoral water withdrawal data availability at the province level was even worse than that at the city level. For example, for 2007, many studies such as Guan et al. (2014)

and Zhao et al. (2015) were still using the 2008 data from the Chinese Economic Census Yearbook as a substitute for 2007 data due to a lack of figures, and these results could suffer from bias as there may have been a structural change in resource use before and after 2008 due to impacts of the global financial crisis (Yuan et al. 2010). Even worse, water withdrawal information was no longer included in the Chinese Economic Census Yearbook 2013, which was the edition following 2008. Similarly, another indicator of agricultural water withdrawal, the cultivated land area, was considered, but I excluded this indicator given that it did not count the number of planting seasons and thus was unable to accurately reflect water withdrawal information.

3.3.2. Comparisons with other datasets

I compared water withdrawal gaps between my estimations and those of a previous study Zhou et al. (2020). I chose 13 Beijing-Tianjin-Hebei cities in 2012, considering these cities were one of the most significantly water-scarce regions. Farming water withdrawals were basically close in these two studies. Total water withdrawal of Zhou et al. (2020) was 2% lower than that of this study on average. For industry, rural- and urban- household water withdrawals, substantial differences occurred between these two studies. For industry, water withdrawal was 10% lower than that in this study on average. For rural household (defined as water withdrawal for livestock and poultry-breeding according to Zhou et al. (2020)), water withdrawal was 22% higher than this study on average. For urban household (including service according to Zhou et al. (2020)), water withdrawal was 57% higher than this study on average.

Because numbers in Zhou et al (2020) did not cover water use for construction and environment and ecosystem, they were at least 93% of the whole water withdrawal amount. Theoretically speaking, in the last column of Table 6, individual gap in each city should be negative, nevertheless total water withdrawals from 7 out of 13 cities have already been higher than in the bulletin statistics. In other words, there arose a contradict.

Total water withdrawal was 4% lower than this study on average. The reasons could be twofold: 1) these data were from different sources between this study (city water resources bulletin) and Zhou et al. (2020) simulation (provincial and national water resources bulletin); 2) there were mergence and separation between cities in historical statistics. This list is in Table 13 of the appendix for detail. I suggest connecting, discussing, communicating about more validation and relevant difficulty, to find a way through cooperation to solve this problem.

Table 6 A comparison of water withdrawal (100 million m^3)

city	farming			industry			urban household			rural household			total		
	Zhou et al. (2020)	this study	gap (%)	Zhou et al. (2020)	this study	gap (%)	Zhou et al. (2020)	this study	gap (%)	Zhou et al. (2020)	this study	gap (%)	Zhou et al. (2020)	this study	gap (%)
Baoding	21.13	22.76	-7	1.58	1.18	34	0.83	1.57	-47	2.13	1.88	13	26.25	31.09	-16
Cangzhou	7.75	9.02	-14	0.52	1.08	-51	1.12	0.74	50	0.86	1.14	-25	11.12	13.91	-20
Chengde	6.17	5.71	8	1.42	1.02	40	1.06	0.80	33	0.96	0.88	9	9.89	9.16	8
Handan	11.48	14.02	-18	1.86	1.83	1	2.93	1.17	150	2.38	1.38	72	20.17	20.72	-3
Hengshui	12.27	12.80	-4	0.81	0.69	17	1.25	0.45	177	1.10	0.66	67	16.05	15.77	2
Langfang	6.11	5.72	7	0.84	0.79	6	2.36	0.86	174	0.59	0.88	-33	11.18	10.26	9
Qinhuangdao	5.49	5.27	4	0.98	0.94	4	1.52	0.71	114	1.03	0.70	47	9.54	8.88	7
Shijiazhuang	19.94	20.69	-4	2.81	2.04	38	2.76	2.38	16	2.39	1.85	30	29.34	31.89	-8
Tangshan	16.95	14.32	18	4.84	4.82	0	2.61	2.29	14	2.41	1.68	44	28.63	25.97	10
Xingtai	13.00	13.29	-2	1.71	1.24	38	1.28	0.69	85	1.24	1.12	10	17.75	18.12	-2
Zhangjiakou	7.97	7.40	8	1.21	0.82	47	1.39	0.51	171	0.78	0.85	-7	11.67	10.56	11
Tianjin	7.11	*	-	5.36	5.10	5	7.29	*	-	1.18	*	-	26.24	23.10	14
Beijing	7.16	*	-	4.90	4.90	0	10.14	*	-	0.58	*	-	28.48	35.90	-21
total	128.27	130.99	-2	28.85	26.45	9	19.10	12.18	57	15.87	13.01	22	246.31	255.33	-4

Note: i) gaps over 10% were indicated in red; ii) * means not announced in bulletin; iii) GDP deflator was calculated as 1.098 times from 2010 to 2012.

For sectoral data, data availability limitation leads to little observed or comparable data. For total amounts, although they are reported directly in official and public statistical bulletins, different bulletins at different administrative level (city and province), or from different governing ministries (Ministry of Water Resources (as in this study) and Ministry of Ecology and Environment (Zhou et al. 2020)) have inconsistence and even contradictive problems. Thus, as Zhou et al. (2020) highlighted harmonizing official statistics of water withdrawal, I summarized different scopes and methods of accounting from various sources in China, as shown in Figure 5. Differences of datasets were put on the left of the x axis while the same points were on the right. Given the fact that calibers in-use were different, only a limited extent of comparison (Chow 2006) were allowed among these datasets.

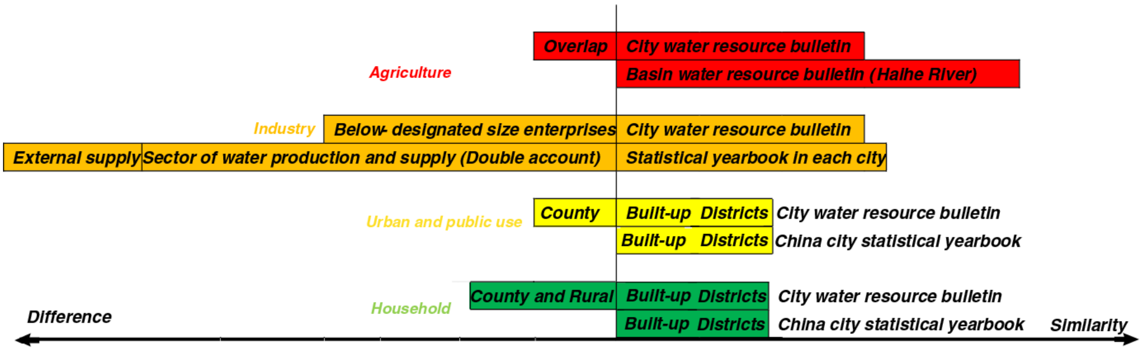

Figure 5 A comparison among different scopes of water-use accounting sectors from various sources in China

First, basin-level water resources bulletins also provide the same sectors of data as city-level bulletins. For example, water resources bulletins of Haihe Basin have data for the cities of Beijing, Tianjin, and Hebei. However, data on agriculture and household water withdrawals in Beijing's are larger and smaller than those from the city-level water resources bulletin, by approximate 60 million m^3, respectively. This difference could be attributed to adjustments that since 2012, cattle water withdrawal has been removed from household water withdrawal and included in agricultural water withdrawal data in the city bulletins. Thus, these two sources may have some overlaps. In addition, regarding household water withdrawal, data from the China city statistical yearbook cover only built-up districts, while city water resources bulletins cover all built-up districts, counties, and rural areas. In this case, I regard data from city-level water resources bulletin as a benchmark to obtain a consistent data source. This makes datasets of this study the most consistent based on available-to-date water statistics in China.

Second, a number of statistical yearbooks at the city level also provide sectoral industrial water statistics. Nevertheless, data availability is quite limited. For example, in 2012, there were merely 59 cities in China that had sectoral industrial water withdrawal data. Moreover, total industrial water withdrawal statistics of yearbook exhibit a discrepancy[14] with those provided in water resources bulletin. Possible reasons may be that 1) bulletin statistics incorporate water withdrawal of enterprises below-designated-size, while yearbook statistics usually cover only enterprises above-designated-size. 2) yearbook statistics include water withdrawal for external supply while bulletin statistics omit this information. 3) water withdrawal in water production and supply sector is regarded as 0 in this study to avoid duplicate accounting: I consider interaction between water production sector and other sectors (as stressed in Hoekstra and Chapagain (2006)). In concrete, this sector is composed of tap water production and supply, and sewage treatment sector. The former supplies water to other sectors; and the latter uses little water (Westerhoff et al. 2005). However, statistical yearbook may double-account water withdrawal in water production and supply sector (Currently there is no method to split this part). Similarly, for yearbook statistics, water withdrawal data have excluded cooling water from rivers, lakes, and seas since 2009, while bulletin data keep this part.

In addition, data from statistical yearbooks are incomparable with data from previous years because the National bureau of statistics has adjusted investigation methods in terms of calibers and periods. For example, according to the China Statistical Yearbook

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[14] In a meaning of ‘inconsistence’.

(Yearbook 2012), data until 2008 cover all state-owned and above-designated size enterprises. After 2008 the coverage of all industries above the designated size is adopted, which refers to enterprises with annual business revenue over 5 million yuan from 2008 to 2010 and over 20 million yuan after 2011. Given these facts, using yearbook data of sectoral industrial water statistics may cause a problem of internal inconsistency and introduce additional uncertainty when compared with water withdrawal of other types.

Third, attention needs to be paid on discrepancies[15] between water supply and water use in China's statistics. While these two are equal in a number of cities (for example Tianjin), water supply is not equal to water use in other cities. This discrepancy could be attributed to loss in water towers or highland pools in distribution pipelines of water supply establishments, such as tap water factories and the secondary pump stations. Besides, there are some systematic uncertainty in the local statistics (Chow 2006). For example, some out-of-production enterprises were removed from China's water statistics. However, whether these enterprises are in the out-of-production state is sometimes determined and reported by the enterprises themselves. Thus, if these enterprises were still in production or at least partially operational during the downtime (The New York Times), water withdrawal compiled and estimated in this study may be under-estimated and thus suffer from a downward bias.

Finally, for service water withdrawal, to find an accurate driving force (size indicator), I also considered proportions of inputs from water production and supply into each service in IO tables, considering most services mainly use tap water (Thompson et al. 2000; Batayneh et al. 2007). I compared this method with the method using sectoral employee number, and found results of IO input were more reasonable. In the calculation, imports of each sector were excluded from original IO table to obtain domestic input; this could depict local economic interactions more reasonably. But no

[15] In a meaning of 'inconsistence'.

more than 20 cities have IO tables in 2012. In sum, IO method would be preferable when more IO tables at the city level are accessible.

3.4. Methods of water availability and scarcity

Due to better data availability and simplicity, as used by water resources bulletins (The Ministry of Water Resources 2019) and Liu et al. (2019b), the net runoff measure was used in this study. I obtained relevant data from water resources bulletins for the cities, referring to Zhao et al. (2019). Quantification of entry water is beyond outline and scope of this PhD-study, although I did acknowledge this amount of entry water was an important part of total water availability for a city. In 2015, China's precipitation (and water availability) was 2.8% (0.9%) slightly higher than, but close to, its average values through multiple years (1957-2000, with statistics) (The Ministry of Water Resources 2019)[16]. The choice of 2015 is mainly due to data availability. Statistics here support the representativeness of 2015 data for values through multiple years.

For methods of water scarcity, I applied the criticality ratio (%) to measure annual water scarcity, referring to Zhao et al. (2015). I only focused on water volume, that is, only quantitative water scarcity was investigated in this study, due to data unavailability of water quality at the city level.

3.5. Summary

Confronted with freshwater scarcity, China has implemented a nationwide and stringent *'Redline'* management regime in the first quarter of 21st century. More and more constraints were imposed on water withdrawal, even in non-arid areas, to promote sustainable water use and economic development. However, as a basic unit to carry out water regulation policies, there is a lack of prefectural-level water withdrawal

[16] Water availability data accounted in this study is for 2015. This sentence is an overview of water situation and 2015 data's representativeness for (comparableness to) values through multiple years. Precipitation may influence water withdrawal and water availability in that year.

methods and data that can be readily obtained, no matter for total or sectoral amounts. Due to the absence of measured efficiencies, it is difficult to quantify water withdrawal or enhance water use efficiencies. Thus, accounting for water withdrawal of different sectors for prefectural cities could help planners know and assess water use. Collating and estimating sectoral water withdrawal data at the city level is a basic first step toward increasing water conservation.

In this chapter, a methodology was developed to estimate the water withdrawal of 65 economic-social-environmental sectors for cities in China based on the China High Resolution Emission Gridded Database and previous water resources bulletins. This methodology can be applied to the different water statistics collected from cities and provinces; six consistent water-use sectors are used, which helped in combining separate water-use data into one consolidated information set.

So far, not all cities in China have the water accounting as routine management activities. Approximately one fifth of 343 cities do not collect or develop water data statistics (with no bulletins). For data of the other four fifths of cities, there are only total numbers of six types provided (with differences in terms of statistical calibers etc., thus my accounting should not be duplicate calculation, but new cases according to specific statistical conditions of different cities). What's more, disaggregated sectoral water withdrawal accounting is not readily available for China. Academic contribution of this study features in selection of 22 driving forces. I connect each size indicator with its unique water-withdrawal efficiency, then develop a novel methodology, based on point-sourced surveys in China. This methodology is suitable for China's own actual state (stated below in detail), which is quite different from developed countries.

Indeed, compared to developed countries, such as Australia, America and France, water accounting in China has already fallen behind. In the historical context of China, even water amount for agricultural irrigation was not metered (The Ministry of Water Resources 2019; Zhang et al. 2020b) , which has been clearly stated in the *2019 National Initiative and Action for Water Saving*. From this angle, there is no mandate legal requirement as developed countries. Additionally, before 2019, water supply capacity was not necessarily considered, and in many places, water was even regarded as a nearly-free resource and withdrawn unlimitedly. In their daily perception, some people from water-sufficient areas even would not pay for water, including drinking water (please refer to discussion in section 1.1). That's also why I focus on China as a developing country. I need to make it suitable for its actual state, rather than fully copying the developed countries.

With regard to water withdrawal accounting method of this study, input data like those of water withdrawal efficiency are monitored data, yet all output data are through modelled estimation from *Case 1)* and *Case 2)*. Thus, this study may be a combination of 'monitored data' and 'modelled estimates'. I think water withdrawal accounting method and data of Zhou et al. (2020) are quite similar. In other words, the methodology of this study is innovative because it combines 'top-down' and 'bottom-up' metrics.

Chapter 4 Accounts of water withdrawal, availability and scarcity for China's prefectures in 2015

Under the general framework in Chapter 3, I accounted for water withdrawal of all 65 economic-socio-environmental sectors for all 343 prefectural cities in China, using a 2015 data benchmark. I first applied it to 18 representative Chinese cities then expanded to all 343 prefectures, and obtained datasets of all 343 prefectures. The data would be transparent for free sharing and public use. As a whole, section 4.1 is based on 18 representative cities and 4.2 is for 343 cities.

4.1. Water withdrawal accounts

I first applied the methodology to 18 cities in 2015, as listed in Table 7. These cities represent 11 provinces, six economic zones, and five regions of China and contain some metropolitan areas (such as the provincial capitals Guangzhou and Chongqing), coastal cities (such as Qingdao), and undeveloped cities (such as Kaifeng) around different basins. Furthermore, I related these cities to the water scarcity assessment according to the method used in Liu et al. (2017). Figure 6 depicts the geographic distribution of these 18 cities and the typical water-use structure of three of them. These three cities are representative in their water withdrawal structure: for agriculture water withdrawal proportions, Guangzhou is the smallest; Xi'an is the largest; and Qingdao is moderate (balance). For simplicity, in the map, *Normal* water scarcity levels (the hatch lines) indicate that there is neither quantity- nor quality-induced scarcity in these cities, *Poor* (the denser hatch lines) indicates there is only quality-induced water scarcity, while *Very Poor* (the densest hatch lines) indicates both quantity- and quality-induced water scarcity. For Liu 2017 method, water scarcity is based on water quantity, pollution/quality at the same time. Water quality method is based on previous paper (Liu et al. 2016). For more information, please also refer to the method developed by Liu et al. (2017) based on Zeng et al. (2013). In total, there were seven cities in the *Poor* classification, ten cities were categorized as *Very Poor*, and one was categorized as *Normal*.

Several characteristics of water withdrawal could be drawn from the perspectives of both city and industry.

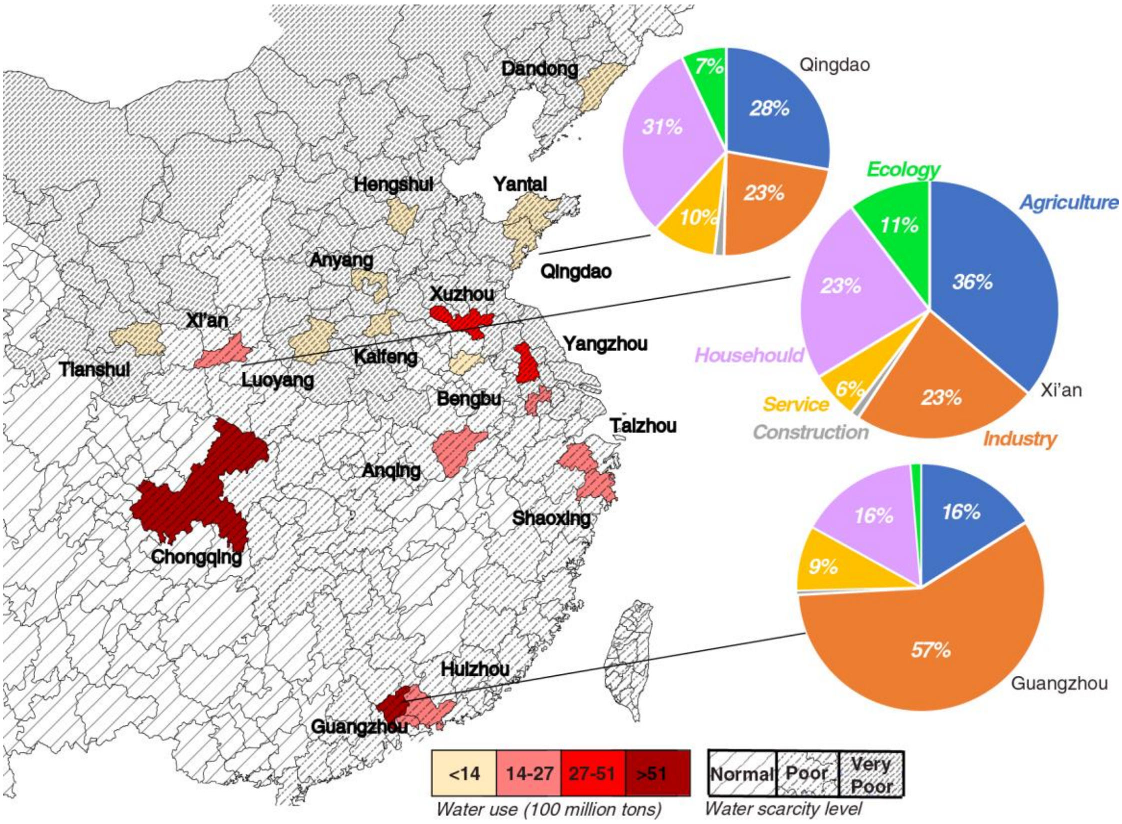

Figure 6 Water withdrawals in 18 representative cities in 2015.

Table 7 shows the water withdrawal index and other socioeconomic characteristics of the 18 cities. Some cities, such as Hengshui, Yantai, and Qingdao, have less water withdrawal per capita and lower water withdrawal intensity than others. Apart from a less water-consumptive production structure (Li et al. 2019b), other reasons for this difference could be that these areas have advanced water conservation technology. For example, Hengshui is aimed to become a pilot city for water conservation in Dec. 2018, and it has broadly applied drip and spray irrigation in modern agriculture parks. There are two above-100,000- metric-ton desalination factories in Qingdao, which represent cutting-edge technology for China. In addition, mulch planting and the integration of water into fertilizer have also been developed in the cities of Yantai and Qingdao city. For more information, see in References (http://www.chinadaily.com.cn/a/201806/29/WS5b35d76ba3103349141dfc75.html) and (http://www.chinadaily.com.cn/m/hebei/2013-07/02/content_16853000.htm).

In Table 7, water withdrawal is from water resources bulletins. GDP per capita and Population are from statistical yearbook of each city. Water intensity, water withdrawal per capita per yr, and household water withdrawal per capita per yr are from my estimation.

Table 7 Water withdrawal and socioeconomic index of 18 representative cities in 2015

City	Province	Representative economic zone	Region	Water scarcity assessment	Ww (10^4 m^3/yr)	Water intensity (m^3/ 10^4 yuan)	GDP /capita (yuan)	Population (10^4)	Ww /capita/yr (m^3)	Household Ww/capita/yr (m^3)
Hengshui	Hebei	Jing-Jin-Ji	North	Very Poor	30095	25	27543	452	67	6
Yantai	Shandong	Central Bohai Bay	North	Very Poor	86900	13	91979	653	133	21
Qingdao	Shandong	Central Bohai Bay	North	Very Poor	87572	9	102519	782	112	35
Dandong	Liaoning	Central Bohai Bay	North	Very Poor	97949	99	40850	239	410	38
Tianshui	Gansu	Western zone	West	Very Poor	37058	66	16956	331	112	17
Chongqing*	Chongqing	Western zone	West	Normal	951360	61	52321	3374	282	40
Xi'an*	Shaanxi	Western zone	West	Poor	182036	31	66938	815	223	52
Huizhou	Guangdong	Pearl River Delta	South	Poor	205924	66	66231	353	584	97
Guangzhou*	Guangdong	Pearl River Delta	South	Poor	661400	37	136188	848	780	122
Shaoxing	Zhejiang	Yangtze River Delta	East	Poor	196219	44	90003	443	443	57
Taizhou	Zhejiang	Yangtze River Delta	East	Poor	188589	53	58917	597	316	45
Xuzhou	Jiangsu	Yangtze River Delta	East	Very Poor	511474	96	61511	1026	498	17
Yangzhou	Jiangsu	Yangtze River Delta	East	Very Poor	396227	99	89647	461	859	60
Kaifeng	Henan	Central zone	Center	Very Poor	131580	82	35326	551	239	21
Luoyang	Henan	Central zone	Center	Very Poor	141300	41	51692	698	202	30
Anyang	Henan	Central zone	Center	Very Poor	143550	76	36828	614	234	32
Anqing	Anhui	Central zone	Center	Poor	270200	191	31101	622	434	35
Bengbu	Anhui	Central zone	Center	Poor	124235	99	38267	374	332	34
Total	11	6	5	3	18	18	18	18	18	18

Note: Ww is short for water withdrawal. * indicates a capital-level city.

From the water withdrawal datasets, I first found following conclusions.

4.1.1. Industrial and household water use may also account for the largest percentages

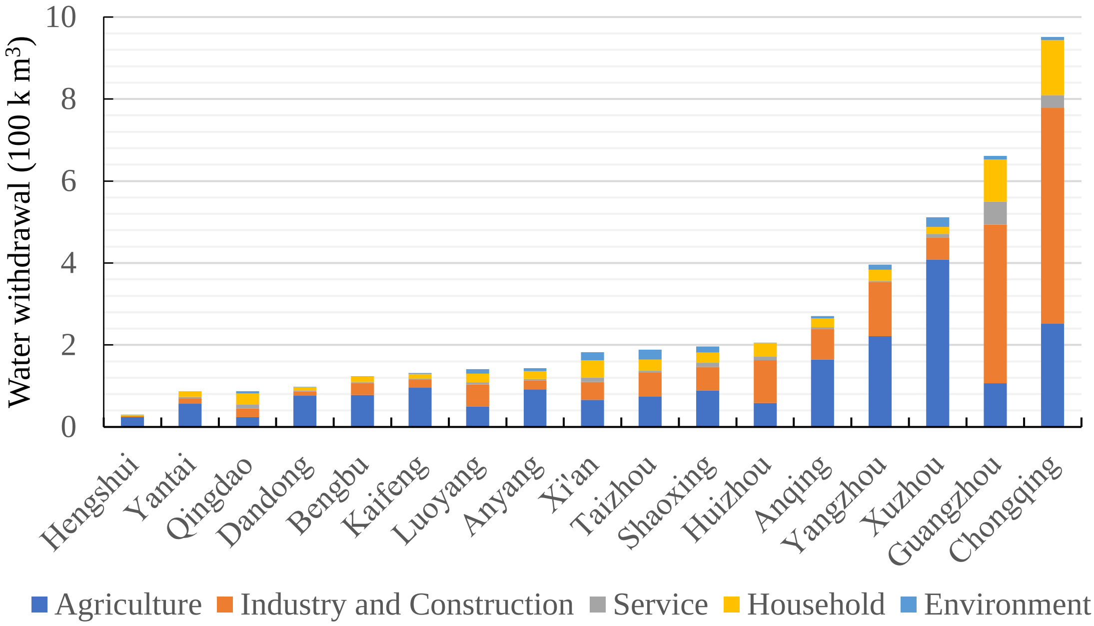

Figure 7 Water withdrawal by city and sector in 2015.

In Xi'an, Shaoxing, Taizhou, Luoyang, and Chongqing, the shares of agricultural water withdrawal are less than 50%, indicating that industry and household water withdrawals in these areas are beginning to dominate the water-use structure.

First, industrial water withdrawal also accounts for a large percentage in the water-use structure of some cities, although the average share of agricultural irrigation is 58.5% across the 18 cities. Contrasting Hengshui and Luoyang, the water withdrawal of agriculture in Hengshui is highest (86%) and lowest in Luoyang (31.4%); conversely, the share of industrial water withdrawal is high in Luoyang (49.7%) and low in Hengshui (7.8%). Second, in Guangzhou and Qingdao, household water withdrawal is greater than agricultural water withdrawal, as shown in Figure 7. This point is also supported by evidence from the China City Statistical Yearbook 2013, as urban household water use accounted for 36% of the total water use for all prefecture cities in China.

Specifically, for industrial water withdrawal, at the city level, industrial water withdrawal accounted for a mean 24% in overall production water-use in 2015. This proportion ranged from 0.24% in Hotan (in northwest China), to over-35% in Shanghai (east), Chongqing (southwest), Nanjing (mid-east) and Fuzhou (south-east), and to 94.83% in Baishan (northeast). Industrial water withdrawals were ranked the first in 17% of cities and the first-two places in 97% of cities among productive water withdrawals. Industrial water withdrawal was mainly driven by large production scales in some cities. For example, industrial output above designated size in Dongguan was the largest and reached 127 million yuan, almost three times of the average of 272 cities. This large output was mainly constituted of communication, electronic machinery and equipment, and electric power, steam and hot water (National Bureau of Statistics 2020)[17].

Similarly, industrial water withdrawal should need notice for regional study, especially for some low water-efficiency processes. I suggest taking stringent regulation actions in processes such as petroleum, coking, and nuclear fuel (with average efficiency (measured by water withdrawal per industrial output) of national sector at 6.3 $m^3/10^4$ yuan (standard deviation=45.2); 70 city-sector combinations in total, No. 26 in *Table 12* of appendix), steel (with average efficiency of national sector at 7.4 $m^3/10^4$ yuan (standard deviation=9.0); 94 city-sector combinations in total, No. 32 in *Table 12* of appendix), chemical (with average efficiency of national sector at 14.1 $m^3/10^4$ yuan (standard deviation=22.9); 131 city-sector combinations in total, No. 27 in *Table 12* of appendix), coal-fired power (with average efficiency of national sector at 43.0 $m^3/10^4$ yuan (standard deviation=55.3); 98 city-sector combinations in total, No. 45 in *Table*

[17] It is a piece of supplementary information to the large industrial output of Dongguan city (127 million yuan). I obtained this information by calculating structure of statistical output of Dongguan city from bureau of statistics.

12 of appendix), textile (with average efficiency of national sector at 18.2 $m^3/10^4$ yuan (standard deviation=38.7); 107 city-sector combinations in total, No. 18 in *Table 12* of appendix), paper making (with average efficiency of national sector at 37.3 $m^3/10^4$ yuan (standard deviation=83.8); 140 city-sector combinations in total, No. 23 in *Table 12* of appendix), building materials (with average efficiency of national sector at 5.1 $m^3/10^4$ yuan (standard deviation=3.6); 114 city-sector combinations in total, No. 31 in *Table 12* of appendix), and food production processes (with average efficiency of national sector at 9.7 $m^3/10^4$ yuan (standard deviation=24.9); 146 city-sector combinations in total, No. 15 in *Table 12* of appendix). Such water intensive processes and sectors should be regulated to improve water management. This is further discussed in the sections 6.1-6.3 of Chapter 6 correspondingly.

Besides, from the datasets I also found total water use structure was ‘balanced’ in a number of cities (that is, water use structure in a city has different parts in an average proportion), nevertheless this could not be a good sign, considering these cities supplied maximum available water amount as cities grew, which should degrade life standards and hinder sustainable economic development.

Table 8 Representative low-water-efficiency processes (and sectors) and their water efficiency index[18]

Low water-efficiency processes	Average water withdrawal per industrial output ($m^3/10^4$ yuan)	Standard deviation	Number of city-sector combinations	Sector code (in *Table 12*)
Petroleum, coking, & nuclear fuel	6.3	45.2	70	26
Smelting & pressing of ferrous metal, including steel etc.	7.4	9.0	94	32
Chemical material & product manufacturing	14.1	22.9	131	27
Production & supply of electricity & hot water	43.0	55.3	98	45
Cloth manufacturing (textile)	18.2	38.7	107	18
Papermaking & paper product manufacturing	37.3	83.8	140	23
Nonmetallic mineral product manufacturing, including building materials, etc.	5.1	3.6	114	31
Food manufacturing	9.7	24.9	146	15

Thus, the control of industrial and urban household water use deserves increased attention. Considering that industrial water withdrawal dominates the water-use structure in some cities, China should manage water during industrialization efficiently and sustainably. In addition, more attention should be paid to cities with higher urbanization rates or better living standards because these factors could make a large difference in household water withdrawal in a city. Thus, controlling urban household

[18] Detailed recommendations and solutions would be given in the following Chapter 6 based on this discussion. Specifically, recommendations are in the section 6.2.2 of Chapter 6 and solutions are in the section 6.3 of Chapter 6.

water withdrawal may become increasingly important for reducing household water use. A number of specifical cities as recommendation are Guangzhou with an urbanization rate at 86.46%, GDP per capita at 156,427 yuan and high urban household water withdrawal at 91,011 10^4 m^3, Chongqing with an urbanization rate at 66.8%, GDP per capita at 75,828 yuan and high urban household water withdrawal at 66,411 10^4 m^3, Qingdao with an urbanization rate at 74.12%, GDP per capita at 124,282 yuan and high urban household water withdrawal at 22,757 10^4 m^3, and Yangzhou with an urbanization rate at 68.2%, GDP per capita at 129,100 yuan and high urban household water withdrawal at 17,242 10^4 m^3 in 2019 etc. (National Bureau of Statistics 2020).

4.1.2. Comparison of top water-use sectors at the city level after agriculture

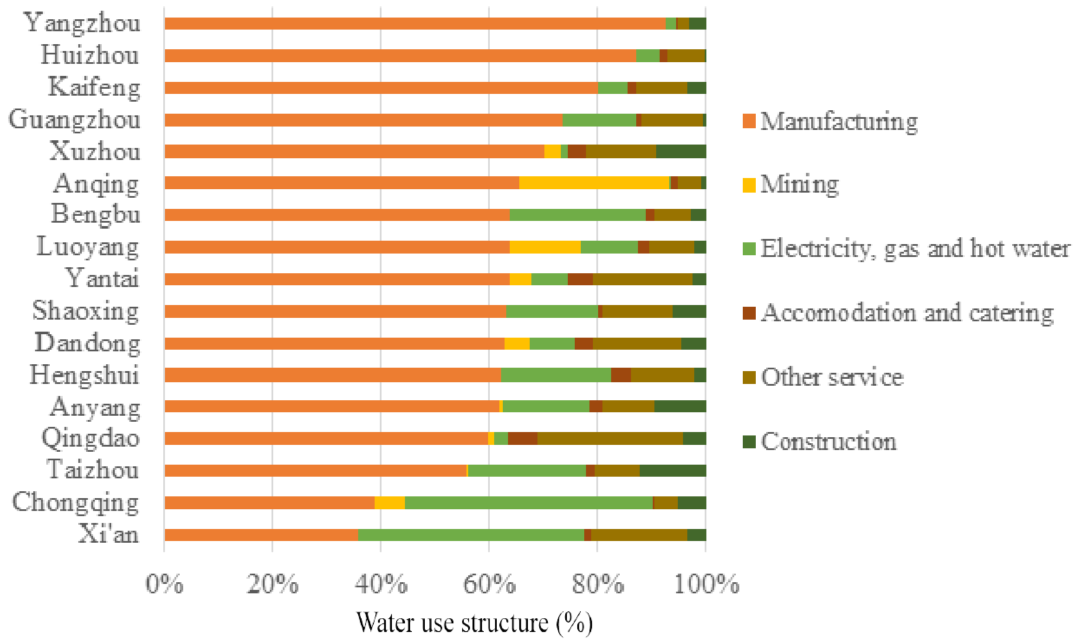

Figure 8 The structure of industry and service water use and the top water-use sectors

Then I make a comparison of top water-use sectors at the city level after agriculture. The principal water-use sectors are similar for different cities. Overall, manufacturing and electricity, gas and hot water take the first two places after agriculture, as shown in Figure 8, although the water in hydropower is also reused by the downstream. I ranked the water withdrawals of the secondary sectors in each city and identified the top three water users for each city, as indicated by the numbers and squares in Figure 9. The production and supply of electricity and hot water (No. 45 in appendix Table 12) is ranked among the top three industrial water withdrawals in 17 of the 18 cities, and raw chemical materials and products (No. 27) is among the top three in eight cities. The most red and yellow squares are located at the upper-right side of Figure 9, indicating the similarity in the water-use industries.

For the industrial sectors, the high users at the city level include smelting and pressing of ferrous metals (No. 32 in Figure 9; and also in appendix Table 12 for full name) and mining and processing of ferrous metal ore (No. 9 in Figure 9), after the production and supply of electricity and hot water (No. 45 in Figure 9) and raw chemical materials and products (No. 27 in Figure 9)[19]. Water is most used in industrial processes, such as mining, processing, cooling, air conditioning, clarifying, and washing (Fan et al. 2019a, 2019b; Li et al. 2019b). Similarly, the three services with the highest water use at the city level are accommodation and catering, education, and public management, social security. The main reason for this finding may be that there is more water-use infrastructure for public services or leisure activities in these sectors (i. e., accommodation and catering, education, and public management, social security) (Gössling 2001), such as bathing, swimming, car washing, piped channels, and other carriers (for example, in schools of education sector (service)).

In sum, the most water-use industries should be targeted at the city level to improve water management. Information from the water inventory provides a window through which different cities can learn from one another in terms of promoting water conservation technology.

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[19] This information is shown in Figure 9 as disaggregated information.

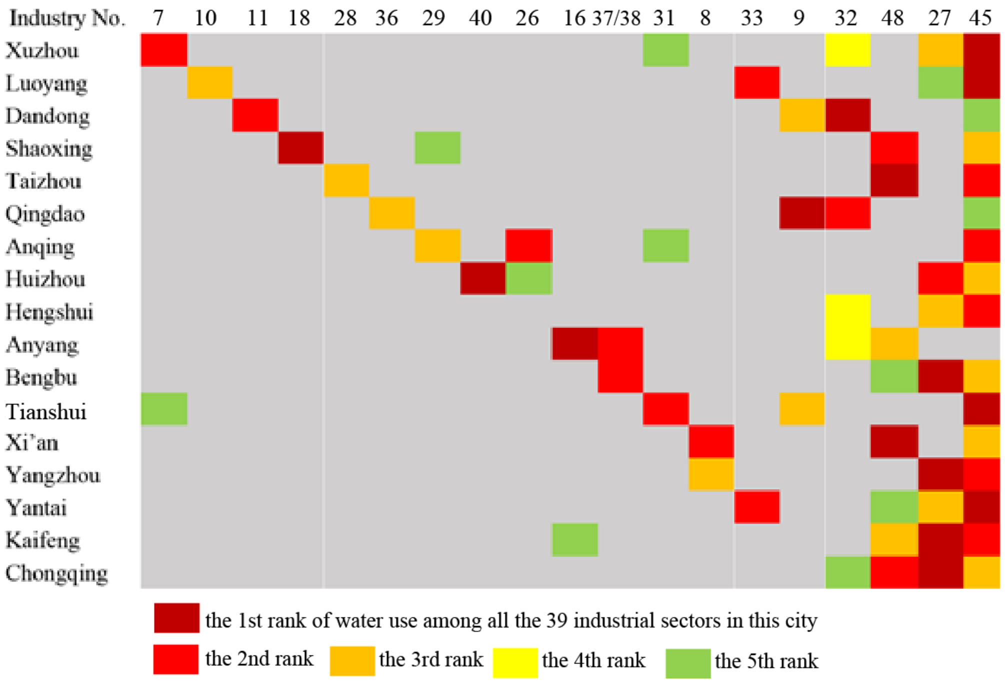

Figure 9 Similarities between the top water-use industries

4.1.3. Significant difference between urban and rural household water withdrawal

The total annual household water withdrawal per capita (AHWUPC) varies from six m^3 in Hengshui to 122 m^3 in Guangzhou; this variation could be attributed to the significant difference in AHWUPC between urban and rural areas, caused by the relatively high urbanization rate and improved living standards in cities such as Guangzhou.

First, I observe that the difference in the AHWUPC in urban areas of different cities is relatively small (as a criterion, I compare this difference to 1) that of total AHWUPC variation and 2) variation of urban vs. rural AHWUPCs, as shown below), especially within a province, due to shared development policies. The AHWUPC in urban areas ranges from 33 m^3/ resident in Anyang to 55 m^3/ resident in Anqing, indicating that the difference in urban AHWUPC from one city to another is not as significant as could have been imagined, which is also the case for the difference in the rural AHWUPC. However, the difference between urban and rural areas is relatively large: the urban AHWUPC is 1.36 times the rural on average and 11 times the maximum in both Bozhou and Lu'an city[20]. From this perspective, it would be meaningful to explore different lifestyles and water withdrawal per capita. Thus, increased attention should be paid to controlling industrial and urban household water use in particular cities.

4.2. Water availability and scarcity accounts

Drawn on the datasets, Figure 10(a) represents a map of total water withdrawal at the city level. Criticality ratio was determined by dividing total water withdrawal (4-5a) by water availability (4-5b) for each city (Zhao et al. 2015; Vörösmarty et al. 2000; Hanasaki et al. 2012). Typically an empirical threshold of 40% is regarded as water scarcity status (Alcamo and Henrichs 2002; Flörke et al. 2013; Wada et al. 2014a), and over-100% as extreme water scarcity stress, signifying that annual water withdrawal exceeds renewable water resources (Liu et al. 2019b). Extreme water scarcity stress indicates unsustainable development: unrenewable water resources would begin to decline, or water transfer projects should be much urgently needed.

Overall, 180 cities (55% of population) were found to be under water scarce conditions. These cities are represented by darker colors in Figure 10(c): Guangzhou and Shenzhen (south), Shanghai, Suzhou, and Yancheng (east), Harbin (north), and Hotan (west). Notably, in contrast to an earlier study (Liu et al. 2019b), I further identified some severe water-scarce areas in south China: Shenzhen (south; 108%) and Foshan (southeast; 107%). Water scarcity in China is known to already be serious, thus caution should be exercised when interpreting the south expansion of scarcity.

Sixty-nine Chinese cities (25%) were found to be under extreme water scarcity. These cities comprised 27% of the population. I identified such cities in different regions (Figure 10(c)), for example Jiayuguan, Kelamayi and Lanzhou (northwest), Panjin (northeast), Puyang and Zhengzhou (central), and Shanghai (east). One of the adverse

[20] In my other future research, I would take other countries' as a benchmark. This is to further check the statement and see whether it is robust.

effects of extreme scarcity was observed in Zhengzhou, where average level of shallow groundwater decreased by 0.5 m in 2015 (The Ministry of Water Resources 2019). Among 13 metropolitan areas containing over-ten-million inhabitants, 12 cities were classified under water scarcity, and 8 under extreme scarcity. Median criticality ratio was 47%, varying between 0.38% in Ganzi (southwest) to over 200% in Jiayuguan (northwest). This median was seven percentages exceeding the scarcity threshold of 40%.

Figure 10 (a), (b) and (c) show a mismatch in distribution between water use and availability at the city level. This mismatch of distributions results in water being commonly over-exploited in northern China. For example, several hotspots (with large water withdrawals) in northwest China, such as Hotan, Kuerle and Bayannur have criticality ratios exceeding 100%. This indicates environmental flow of natural runoff and ecosystem survival (Jacobsen et al. 2012; Van Vliet et al. 2013; Liu et al. 2016) is largely compromised. Figure 10 (d) shows city economic classifications and their spatial distribution. I classified cities into six broad groups, namely: agriculture-based, energy production, heavy manufacturing, light manufacturing, high-tech and service-based cities, using a clustering methodology (Shan et al. 2018).

Overall water scarcity status was poor. This indicated a need of improving water use management. Average water withdrawal per GDP at the city level was at 7.4 m^3/k yuan. This still had a gap compared with global average at 4.9 m^3/k yuan. Thus, there still should be much potential in reducing water withdrawal. Among 272 cities, 40 prefectures with the largest amounts accounted for approximately 50% of water resources. 146 cities, with over-55% populations and 53% industrial sectors, suffered from high water scarcity. Criticality ratio of Xuzhou, Linyi, Jining and Shangqiu were the highest.

These denoted a harsh water scarcity situation. As an interesting and old saying *'Jiulongzhishui'* goes, more-than-enough institutions and departments are involved in water use regulations at the same time, but cannot enforce them effectively. This could be attributed to ambiguous rights and obligations. For example, the Ministry of Housing and Urban-Rural Development is in charge of urban water supply and conservation (MOHURD 2020), while the Ministry of Water Resources is also responsible for protecting natural water resources (The Ministry of Water Resources 2019). Their rights and obligations are overlapped (i. e., 'urban water supply and conservation' and 'protecting natural water resources' are overlapped to some extent), and thus should be clarified further.

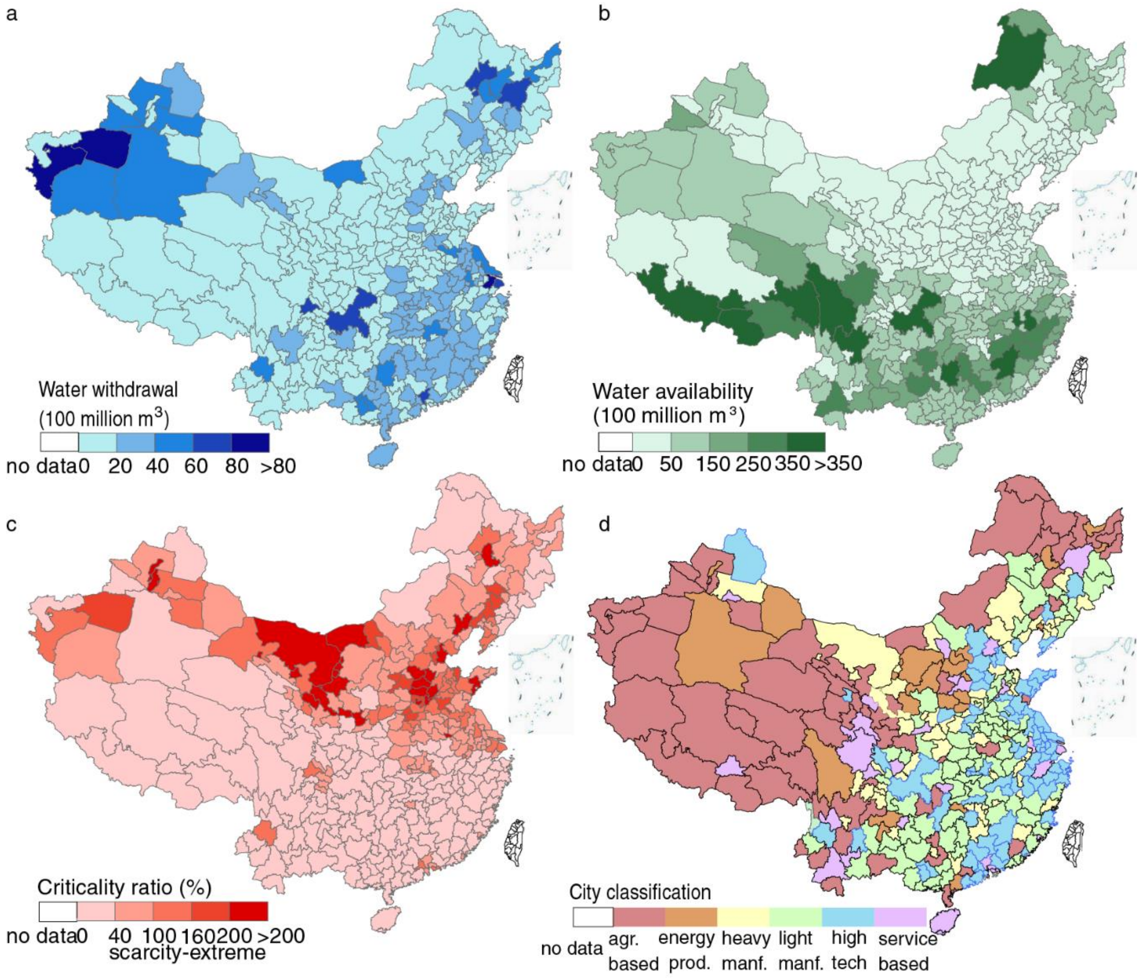

Figure 10 Prefecture-level cities and their water situation based on 2015 data. (a) total water withdrawal, (b) total availability, (c) criticality ratio, and (d) groups of representative sector clustering

Note: Average size of cities was 2.80 million ha; average population was 4.43 million.

I observed cities in their corresponding provinces for a robustness check and found similar results. In Figure 11, statistics of 18 provinces are arranged in the order of decreasing water scarcity levels (left axis). The number in the parentheses is the average ratio in a province (right axis). Meanwhile, the red bars indicate CR is increasing in this province compared to 2014, while the green bars indicate CR is decreasing. Overall speaking, only 6 out of 18 provinces were lower than 40%, and 5 higher than 100%. Water-scarce cities and provinces should be more careful in water conservation because they may need to buy and transport more water from their neighbors in future. These 18 are basically in *Case 1* of the methodology, i. e., for cities with full water withdrawal statistics, and with little uncertainty for total water withdrawal of each of their cities.

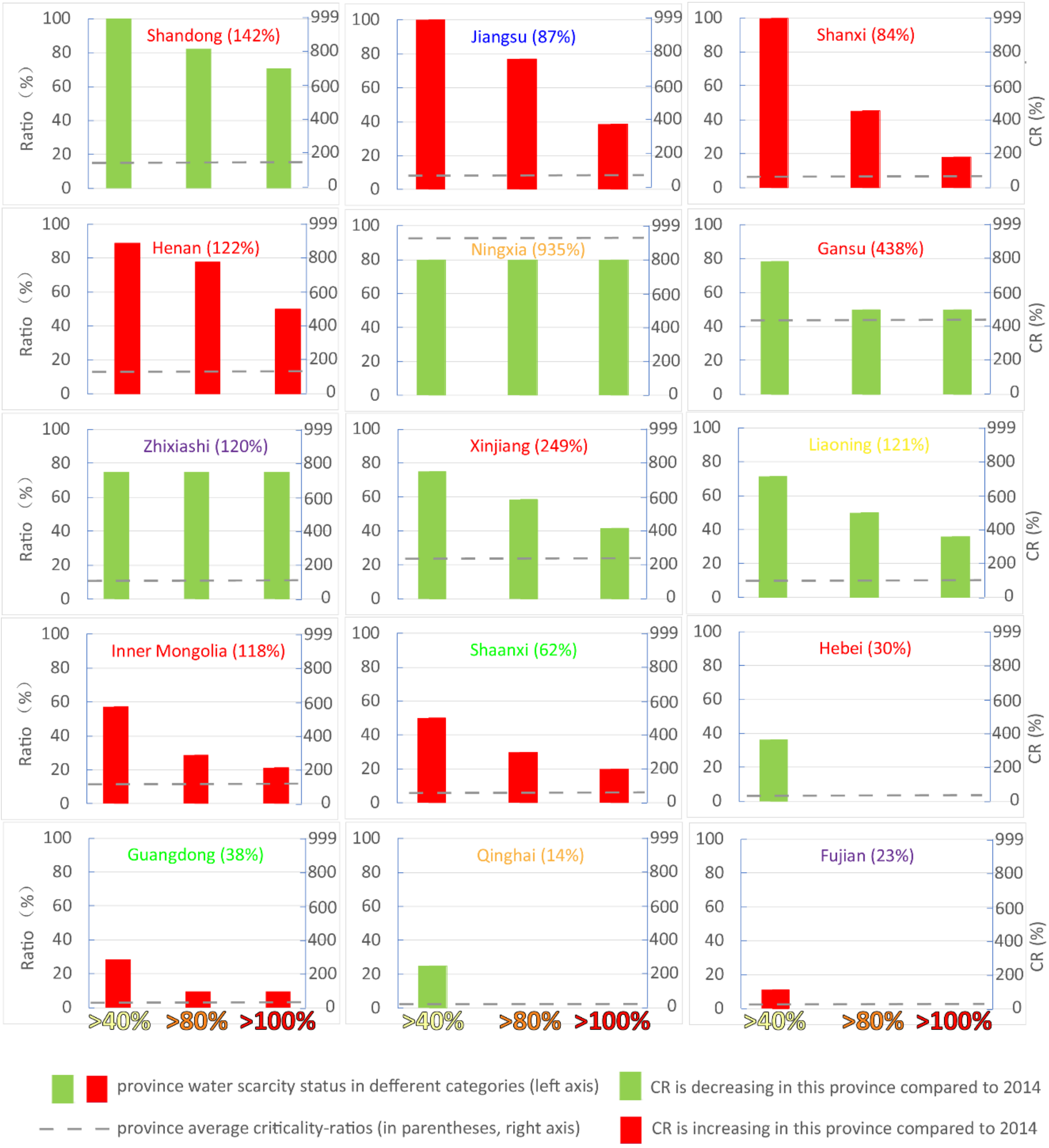

Figure 11 Provincial water scarcity status in 2015 (ranked from severe to low water stress, in left axis) and average criticality-ratios (right axis).

4.3. Summary and outlook

Under the general framework, I accounted for water withdrawal of all 65 economic-socio-environmental sectors for all 343 prefectural cities in China, using a 2015 data benchmark. I first applied it to 18 representative Chinese cities then expanded to all 343 prefectures, and obtained datasets of all 343 prefectures.

Based on the inventory, I identified some characteristics of water withdrawal from the perspectives of both the city and the sector, and provide policy implications, which aimed at addressing concerns about the current and future state of water resources in China and helping to combat the water crisis. From the water withdrawal datasets, I first found 1) Different from conventional perceptions that agriculture is usually the largest water user, industrial and household water withdrawal may also account for the largest percentages in the water-use structure of some cities. 2) The difference among annual household water use per capita in the urban areas of different cities is relatively small (as is the case for rural areas), but that between urban and rural areas is large. Thus, increased attention should be paid to controlling industrial and urban household water use in particular cities.

The data accounted could be used directly in input-output models, consumption-based accounting and structural decomposition analyses. These analyses would help gain in-depth insights into sectoral water-saving priorities, industry transfer and market restrictions to develop a water-saving society. For market restriction policy, introduction of technology and industries, and sales of products, should be based on how much water a local city has, and whether their relevant water efficiency performance could meet local standards, otherwise it should only be eliminated or transferred to somewhere with looser restriction. For example, some industries in Beijing have already been relocated into surrounding provinces, in accordance with geographical endowment of water resources. This policy could be matched with water label policy. Representative products of policy promotion are household appliances, such as toilet, faucet and shower. Then this policy should be extended to agriculture, industry and commercial equipment.

Besides, these inventories would facilitate regional water-status education and training. All data would be transparent for free sharing and public use. This should be of significance and need great attention, because water scarcity indicates the most serious conflicts between demand and supply. What drives the large demand, whether and how is this met, what is the impact of such large resources' consumption? These are important especially when large and dense population in rural China suffering from potable water insecurity is taken into consideration (Liu et al. 2021). This PhD study showed 180 cities and 55% of population in China were found to be under water scarce conditions. Sixty-nine Chinese cities (25%) were found to be under extreme water scarcity. These cities comprised 27% of the population in China. The water scarcity data at the city level could provide a preliminary reference for these questions and future industry regulation to alleviate water scarcity. China water management in this regard is quite weak. The improvement in this study should be a much-needed step forward.

Chapter 5 Awareness of sectoral water saving in water-stressed cities

Through these high-resolution water scarcity accounts I first identified water-stressed cities and low water-efficiency sectors at the city level. This is important because these sectors of low efficiency in water scarce cities should be well-targeted to save water, under the *'Redline Regulation'* of water withdrawal efficiency improvement. Through unique account, I proposed that awareness of sectoral water savings should be given greater focus in water scarce cities to prevent the situation to get worse. Sectoral water saving should be well placed to save water in water scarce cities.

This chapter is aimed to show that more focus is needed to raise awareness of water savings in specific sectors, for both the opportunity to do so, and the potential savings from doing so (Chapter 6). This chapter lays a theoretical basis for Chapter 6. In this chapter, from accounts on water withdrawal, availability and scarcity, I found the following conclusions.

5.1. Greater focus on sectoral water saving in water-stressed cities

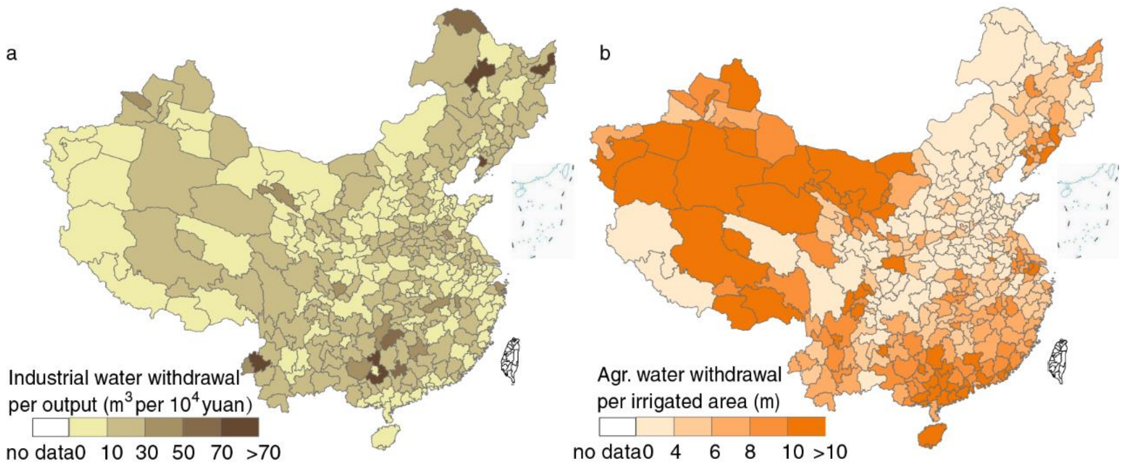

Figure 12 Water withdrawal intensities of cities based on 2015 data. (a) industrial water withdrawal per output, and (b) agricultural water withdrawal per irrigated area

Note: Average size of cities was 2.80 million ha; average population was 4.43 million.

Awareness of sectoral water savings should be given greater focus in water scarce cities to prevent the situation to get worse. One might expect industries in water scarce cities to adopt water saving technologies, hence their water withdrawal intensities should be lower than comparable industries in water sufficient areas. In other words, water scarcity should force local industries to be front-runners in water use efficiency improvements. Unlike this hypothesis, I found that a few water scarce cities (Figure 12(a)) such as Qiqihar (north), Yingkou (east), Wuhai (west) and Puyang (central), had water intensities much higher than in cities abundant in water resources. Although China has set intensity reduction redlines since 2011, reducing intensities of sectors in water-scarce cities should therefore be prioritized. Cities such as Wuhai, Hegang, Puyang, and Qitaihe, had water intensities which were still high, and they were not known to be over-exploiting resources until 2018 (Wang et al. 2019).

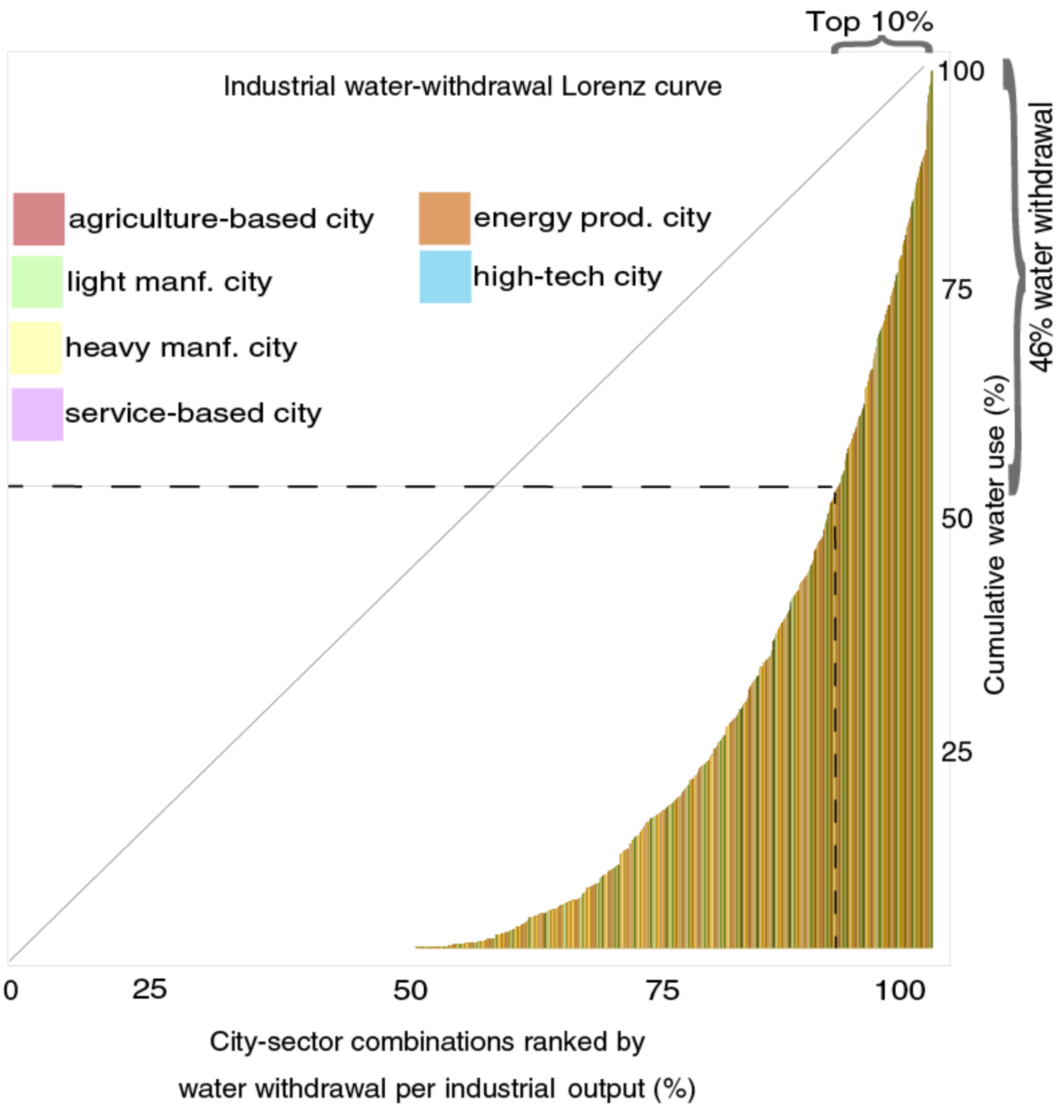

Figure 13 Sectoral water-withdrawal Lorenz curve depicted by different intensities of a total of 41×272=11,152 industrial sector-city combinations from six groups

A disproportionately small fraction of sectors at the city level contributed to large water withdrawals. Sectors of low-efficiencies should be targeted to save water. Taking industrial related sectors for instance, I ranked a total of 41×272=11,152 sector-city combinations by order of water intensity from low to high, and then calculated cumulative water withdrawal accordingly. I depicted these shares relative to shares of cumulative numbers of sectors and obtained a water-withdrawal Lorenz curve for illustration (Figure 13). The curve indicates that the top 10% of high-intensity sectors account for 46% of water withdrawal, as a disproportionate fraction. Such high-intensity water users were in cities with representative industries such as papermaking and product manufacturing in Chenzhou (central), Lincang (southwest) and Qiqihar (northeast); liquor, beverage and tea manufacturing in Jingdezhen (mid-east), Anqing (mid-south) and Wuzhou (southwest); and electricity and hot water supply in Changde (mid-south). These water scarce cities with sectors of low water-withdrawal efficiencies should be targeted.

5.2. Sectors of high water-withdrawal intensity exist in small developing cities

Based on the datasets, I further identified industrial and agricultural sectors with high water-withdrawal intensity (per output and per irrigated area). They were mostly in small developing cities. Quantitative characterization for intensities and their ranges in industrial related sectors were summarized in Table 9. I hypothesized a normalized distribution of intensity in each of 41 industrial related sectors. With a three-standard-deviation method, I obtained reasonable intervals of intensity. I regarded extremes beyond these intervals as outliers of intensity then excluded extremes (Rau et al. 2020). For example, 42 sector-city combinations were excluded in farming due to extremes of water withdrawal efficiency.

Based on these data, I firstly found sectors with high intensity. Production & supply of electricity & hot water, paper products and mining and processing of ores (nonmetal, ferrous and nonferrous metal ores) were amongst sectors with the highest intensity. Such sectors may exhaust water through production such as mining, processing, scrubbing, cooling, and washing and they should be restricted or reduced in future to save water. I suggest taking stringent regulation actions in recommended city-sector combinations with the lowest efficiency, such as production & supply of electricity & hot water in Nanjing city (in Jiangsu province), Neijiang city (in Sichuan province), and Nanchong city (in Sichuan province), with water efficiency (measured by water withdrawal per industrial output) at 204, 172, 183 $m^3/10^4$ yuan, respectively; Papermaking & paper product manufacturing in Tacheng city (in Xinjiang province), Guilin city (in Guangxi province), Yan’an city (in Shaanxi province) and Handan city (in Hebei province), with water efficiency at 279, 263, 255 and 255 $m^3/10^4$ yuan, respectively; Mining and processing of nonmetal ores in Changde city (in Hunan province), Chuxiong autonomous prefecture (in Yunnan province), and Beihai city (in Guangxi province), with water efficiency at 219, 204, and 168 $m^3/10^4$ yuan, respectively; Mining and processing of ferrous metal ores in Zhangzhou city (in Fujian province), Nanjing city (in Jiangsu province), and Yangjiang city (in Guangdong province), with water efficiency at 199, 194, and 146 $m^3/10^4$ yuan, respectively; Mining and processing of nonferrous metal ores in Fuzhou city (in Jiangxi province), Qiannan autonomous prefecture (in Guizhou province), and Quanzhou city (in Fujian province), with water efficiency at 133, 132, and 123 $m^3/10^4$ yuan, respectively.

What is more, such high-intensity water withdrawers were mostly found in small developing cities, such as Nanchong, Zhuzhou and Fuzhou (in Jiangxi province) in industrial related sectors; Zhoukou, Linyi and Fuyang in agricultural sectors. In contrast, other cites had more low-intensity sectors, such as Shenzhen, Tongliao, Rizhao and Fushun in industrial related sectors; Kelamayi in agricultural sectors. At the same time in the criticality ratio column of Table 10, I also found these high-intensity cities being constrained by high (and extreme) water scarcity. They produced with advanced water-saving technology, and built a water-saving economy (Cheng and Li 2021). For example, although water withdrawal-to-availability ratio in Tongliao was 80%, meaning high water stress, nevertheless, sufficient economy growth (7.8% GDP growth rate, higher than average) was supported due to advanced water-saving irrigation technology and structure in 2015 (Wei et al. 2016). Due to city transition, conventional industrial and northeastern cities, such as Harbin, Daqing and Changchun, were less water-intensive than those southern cities, e. g. Ningbo, Shaoyang, Jingdezhen, Jiujiang, and Baoshan. Additionally, these intensities and ranges of top- and bottom-cities could be referred as standard intra sectors.

Table 9 An index of top-5 industrial related sectors of high water-withdrawal intensity and their representative cities

High intensity sectors (top 5)	Average intensity (m^3/ k yuan)	Standard deviation	Range (m^3/ k yuan)	Number of sector-city combinations	Representative cities (intensity)	
					Top 5 (m^3/k yuan)	Bottom 5 (m^3/k yuan)
Electric power, steam & hot water	4.30	5.5	[0, 20.8]	254	Nanjing (20.4), Luohe (13.4), Binzhou (11.1), Nanchong (18.3), Neijiang (17.2);	Leshan (0.16), Zhenjiang (0.15), Wuwei (0.16), Ningde (0.06), Ganzhou (0.01);
Paper products	3.73	8.4	[0, 28.8]	215	Guilin (26.3), Handan (25.5), Hengyang (23.4), Taiyuan (24.2), Xi'an (25.1);	Tongliao (0.22), Shenzhen (0.02), Benxi (0.01), Beijing (0.17), Ankang (0.05);
Mining & processing of ferrous metal ores	3.47	5.7	[0, 20.6]	128	Nanjing (19.4), Zhangzhou (19.9), Fuzhou (13.9, Jiangxi), Zhuzhou (13.5), Quanzhou (12.5);	Rizhao (0.002), Mianyang (0.05), Wuhan (0.001), Liuzhou (0.003), Linyi (0.01);
Mining & processing of nonmetal ores	3.05	7.9	[0, 26.9]	117	Changde (21.9), Fuxin (13.7), Wuwei (12.2), Zhuzhou (15.1), Anqing (13.1);	Suizhou (0.01), Yangjiang (0.01), Xinyang (0.01), Xiangtan (0.01), Lu'an (0.003);
Mining & processing of nonferrous metal ores	2.26	3.7	[0, 13.4]	124	Fuzhou (13.3, Jiangxi), Ganzhou (12.1), Suizhou (11.9), Wuzhou (10.6), Lishui (10.6);	Akesu (0.15), Fushun (0.12), Suzhou (0.02), Shaoxing (0.16), Linfen (0.04)

Note: industrial output was used to estimate water withdrawal intensity.

5.3. Awareness of special water saving accounting for water-stressed cities to improve sectoral efficiency

China should improve its water statistics and specially prepare annual water saving accounts for water-stressed cities. I even find it is much harder to compile the bulletins of northeast three provinces, Liaoning, Jilin, Heilongjiang (indicating a need for improving water conservation attention and management); on the contrary, some water-sufficient cities (those in Zhejiang provinces) are more advanced in water data quality and publicity, thus as well as water conservation.

Water accounts can be applied to improve sectoral water-withdrawal efficiency, and investigate the impacts of changes in water resource allocation and use, including assessment of the influence of structural changes and economic development (such as Jia et al., 2004; Cole, 2004), the driving forces from different industries behind particular water problems (Vörösmarty et al. 2000; Rijsberman 2006), and the sectoral impacts of water regulation (including charges and incentives) (Jønch-Clausen and Fugl 2001; Saleth and Dinar 2000). Historically, due to a lack of disaggregated water data at the sector or city level, this type of research was insufficient, but it now has the potential to be developed.

Table 10 Water scarcity classes and representative cities through accounting

Scarcity class	Representative cities
Extreme water scarcity (criticality ratio>100%)	Jiayuguan, Yinchuan, Bayannaoer, Karamay, Lanzhou, Shijiazhuang, Hengshui, Puyang, Qingdao, Daqing, Tangshan, Alxa, Liaocheng, Qinhuangdao, Hebi, Xianyang, Tianjin, Dongying, Shenyang, Zhengzhou, Baotou, Jiaozuo, etc.;
High water scarcity (40%<criticality ratio<100%)	Panjin, Zaozhuang, Zhoukou, Changchun, Linfen, Shangqiu, Nanjing, Ordos, Datong, Chifeng, Luoyang, Urumqi, Tongliao, Xi'an, Luohe, Linyi, Xiangyang, Jinzhong, Rizhao, Guangzhou, etc.;
Medium water scarcity (20%<criticality ratio<40%)	Fushun, Bayingoleng, Quanzhou, Suizhou, Zhuhai, Changsha, Nanchong, Baoding, Fuzhou, Yili, Baoji, etc.

In addition, water inventory data could help local water users better comply with the Three-Redline regulations because it is difficult to reach a target without comparable water use numbers. Data would also increase transparency because in China, some officials with responsibility for water use may feel pressure to reveal water-use data to the public because these data are included in the performance evaluation system for political promotion, and they care about their own achievement. For details, see in References (https://time.com/3848171/china-environment-promotions/).

5.4. Summary

Through unique high-resolution water scarcity accounts, I first identified water-stressed cities and low water-efficiency sectors at the city level. These sectors of low efficiency in water scarce cities should be well-targeted to save water, under the *'Redline Regulation'* of water withdrawal efficiency improvement. I proposed that awareness of sectoral water savings should be given greater focus in water scarce cities to prevent the situation to get worse. To some extent, this is a new water saving strategy, not merely about the current water saving measures.

From accounts on water withdrawal, availability and scarcity, I found 1) The top 10% of low-efficiency industrial related sectors represent 46% industrial water withdrawal. 2) Agricultural and industrial sectors with high water-withdrawal intensity existed in representatively small developing cities. Thus, attention should also be paid to both coordinating production scales in water-scarce cities, and reducing water withdrawal intensities for stringent management. In sum, China should specifically prepare annual water accounts at the city level and establish a timetable to tackle water scarcity, which is a basic step toward efficient and sustainable water crisis mitigation. Information of water inventory would also provide a window for cities to learn from each other in terms of smaller water use intensities in all types and a promotion in water conserving technology.

Chapter 6 Sectoral water saving under China's *'Redline Regulation'*

6.1. Water-saving scenarios in 41 industrial and 5 agricultural sectors in 180 water-scarce cities

To investigate sectoral water-saving potential and implication for alleviating stress, I built water-saving scenarios in 41 industrial and 5 agricultural sectors across 180 water-scarce cities, by assuming a convergence of below-average efficiencies to the national sector-average by technology improvement.

For scenario analysis in industrial and agricultural sectors, I substituted above-average water intensities with average ones, by assuming technical progress in water use efficiency would enable low-efficiency sectors to reach the average value. In fact, a number of cities even require sectors to implement the most up-to-date technologies or regulatory standards for water savings in production. Scenario A was in 5 agricultural sectors for water-stressed cities; and B was in 41 industrial related sectors for water-stressed cities.

If water withdrawal intensity of a sector in a city was lower than the national sector-average, I left its water intensity as it was; If the intensity of a sector was higher than the national sector-average, but it occurred in a city with no water stress (criticality ratio less than 40%), I did not substitute it either; Only for sectors that both had above-average intensities and were located in water-stressed cities, I did substitute intensities with national sector-averages.

I think average of national sector would be useful, considering that I found some extreme high-intensity sectors during the survey, and that there was high heterogeneity of water use and saving technology across cities for the same sector (Zhang et al. 2020b). In fact, technology is a vital factor underpinning different intensities in the same sector. For example, in Suzhou, electricity and hot water supply consumed as much as 5.3 km^3 p.a. (64% of total water use) due to once-through cooling technology (water-intensive) accounting for 99% of thermal plants. Conversion of these plants to circulating cooling technologies, would result in large water savings. In contrast, food or general-machinery manufacturing in Dongguan and Hanzhong, which stood out as high-efficiency exemplars, should be set as demonstration sites for peers in the same sector.

6.2. Targeted sectors and cities for water saving based on efficiency improvement

In water scarce cities, in total I estimated 69.2 km^3 (±2.56%) water savings could be achieved. This amount is equivalent to the annual water demand of Russia in 2015 (FAO 2019), almost four years' demand of Hebei province of China (FAO 2019), and more than 3,000 times the water storage capacity of the West Lake in Hangzhou, China.

6.2.1. Water saving potential in agricultural sectors for water-stressed cities

In agricultural sectors, a relatively small fraction (10%) of 5×343=1,715 sector-city combinations contributed to large (70%) of total agricultural water savings. An amount of 50.3 km^3 (±2.32%) of water would be saved (*Figure 14*(a)). For individual city, water savings ranged from 26,553 m^3 in Xinzhou, to 6.5 km^3 in Kashi. *Figure 14*(b) illustrates rice cultivation towards right-hand side of x-axis could contribute approximately 25% water savings, whilst maize cultivation on the left could contribute a 14% reduction.

Furthermore, large contributors were a few sectors at the city level, such as sectors in rice, as shown in *Figure 14*(c) (above the dotted line), whilst it was less effective to tap saving potential for sectors below the dotted line. Typically, there will be more than a single city-sector combination affected in most sectors. Jiang (2009) recommended exploration of cost-effective and long-term saving options by considering disruptions caused to economy. Due to better data availability, number of sectors was used in this study. Here I hypothesized that the fewer sectors substituted, the less economic disruption would result. In other words, I assumed a positive correlation: the greater number of sectors disrupted, the more cost of water conservation measures is, considering more human and material resources have to be input and managed[21].

Interestingly, a minority of sectors could save most water whilst affecting fewer cities[22]. This seems a win-win opportunity between economy and water-resources. Instead, most sectors needed to disrupt economical activities and bring a significant cost to economy to achieve the same saving. From a sectoral water usage perspective, I therefore recommended water saving initiatives in 3 key sectors which potentially contributed 70% of the available water savings: rice cultivation (25%), vegetables and fruits cultivation (25%) and fiber and bean etc. cultivation (20%). For example, rice cultivation contributed to 25% (~12.3 km^3) in total agricultural water saving, yet these sectors accounted for just 20% of overall substituted sectors at the city level. These sectors and cities should be prioritized. Requiring all sectors to evenly or in-general improve water efficiency does not therefore represent an optimal policy choice.

A list of targeted sectors and cities is provided in Table 11, such as Daqing (Heilongjiang province, northeast), Suzhou (Jiangsu province, southeast) and Chengdu (Sichuan province, southwest). Cities with large water-saving potentials are not limited to any specifically geographic regions, indicating efficiencies would be improved unbiasedly. This finding also applies to industry water saving (Scenario B, *Figure 14*(d) and (e)). In 6-1(b) and (d), uncertainty arose from treatment of extreme high-intensity sectors during the survey, considering high heterogeneity of water use and saving technology across cities for the same sector (Zhang et al. 2020b) (eventually I verified general influence of these extremes on total water saving was approximately 6 billion m^3 more than values of scenarios excluding extremes). In *Figure 14*, grey shading indicates specific range of intensities (empirical distribution) in each sector. Upper and

[21] Yet I acknowledge that using 'number of sectors' as a proxy for the cost of sectoral water saving strategy should be only one of the many possible patterns or ways. This is mainly limited by data unavailability of sectoral value-added, or employment in this study. Data availability of sectoral number is better.

[22] This minority of sectors were '3 key sectors which potentially contributed 70% of the available water savings: rice cultivation (25%), vegetables and fruits cultivation (25%) and fiber and bean etc. cultivation (20%)' (explained in the following 4th line). The majority of sectors were the other sectors (city-sector combinations) in agriculture.

lower boundaries were calculated by the three-standard-deviation method. For brevity, I listed a product and a code in each sector; 1-5 are crop cultivation, 7-13 represent mining and processing, 14-44 are manufacturing, and 45-47 are production and supply of electricity, gas and hot water. For full names and descriptions please refer to appendix I. I did not include sectors of small contributions. And I only consider farming and exclude forestry, animal husbandry and fisheries in agriculture of Chapters 6-7.

Table 11 An index of top sectors and cities with above-average water saving potential

Industrial or agricultural sector	City	Province	Criticality ratio (%)	Industrial output (bn y) or Irrigated area (10^3 ha)	Water saving potential (10^6 m^3)
Cloth manufacturing	Guangzhou	Guangdong	74	28	177
	Shantou		58	28	90
	Zhongshan		69	17	61
	Nanyang	Henan	60	49	59
	Pingdingshan		115	8	57
	Huai'an	Jiangsu	62	30	109
	Suzhou		127	136	720
	Anshan	Liaoning	57	11	79
Chemical material & product manufacturing	Xiangyang	Hubei	77	38	89
	Xiangtan	Hunan	51	13	224
	Taizhou	Jiangsu	77	133	50
	Tongliao	Inner Mongolia	81	19	59
Electricity & hot water supply	Hefei	Anhui	59	40	51
	Nanjing	Jiangsu	87	19	294
Rice cultivation	Huainan	Anhui	230	117	439
	Daqing	Heilongjiang	291	352	847
	Baicheng	Jilin	92	251	403
	Lianyungang	Jiangsu	151	303	454
	Nanjing		87	156	455
	Nantong		65	407	659
	Suzhou		127	124	427
	Xuzhou		150	543	693
	Yancheng		61	704	664
	Yangzhou		105	246	492
Vegetable & fruit cultivation	Panjin	Liaoning	99	47	463
	Chengdu	Sichuan	118	215	765
	Wuwei	Gansu	156	50	483
	Bayannur	Inner Mongolia	1106	17	4,436
	Akesu	Xinjiang	163	620	1,335
	Kashi		144	924	1,596

Note: as summarized in *Figure 14*, these should be targeted in future water saving policy interventions.

6.2.2. Water saving potential in industrial related sectors for water-stressed cities

In industrial related sectors, reducing high water intensities in a small fraction (25.7%) of the 11,152 sector-city combinations would result in large (63%) of total industrial water savings. An amount of 18.9 km^3 (±3.2%) water would be saved. This equates to annual water demand of Australia or Hebei province of China, and almost 1,000 times the West Lake capacity. For individual city, water savings ranged from 118,700 m^3 in Beijing, to 2.0 km^3 in Guangzhou. I hypothesized industrial value-added levels remained unchanged, in which case water withdrawal per value added would decrease by 20%, equating to the 2015-20 efficiency redline of improvement. I identified four sectors (*Figure 14*) which contributed to almost half of total industrial water savings: cloth manufacturing, chemical material and product manufacturing, clothing manufacturing, and electricity and hot water supply. These detailed recommendations are in furtherance of discussion in the section 4.1.1 of Chapter 4.

Notably, in contrast to conventional understanding (Zhang et al. 2020b), electricity and hot water supply was not the largest contributor to water savings. The largest potential was in the cotton/fiber-cloth-clothing supply chain, including from cotton to intermediate products, i. e., fiber, yarn, cloth and other materials in textile, and from fiber and yarn etc. to final clothing products such as apparels, footwears, hats, masks, and trims. This finding is supported by a previous study (Niinimäki et al. 2020), and could be useful in water saving regulation for relevant industrial committees. Similarly, manufacturing of chemical materials and products would also bring greater savings.

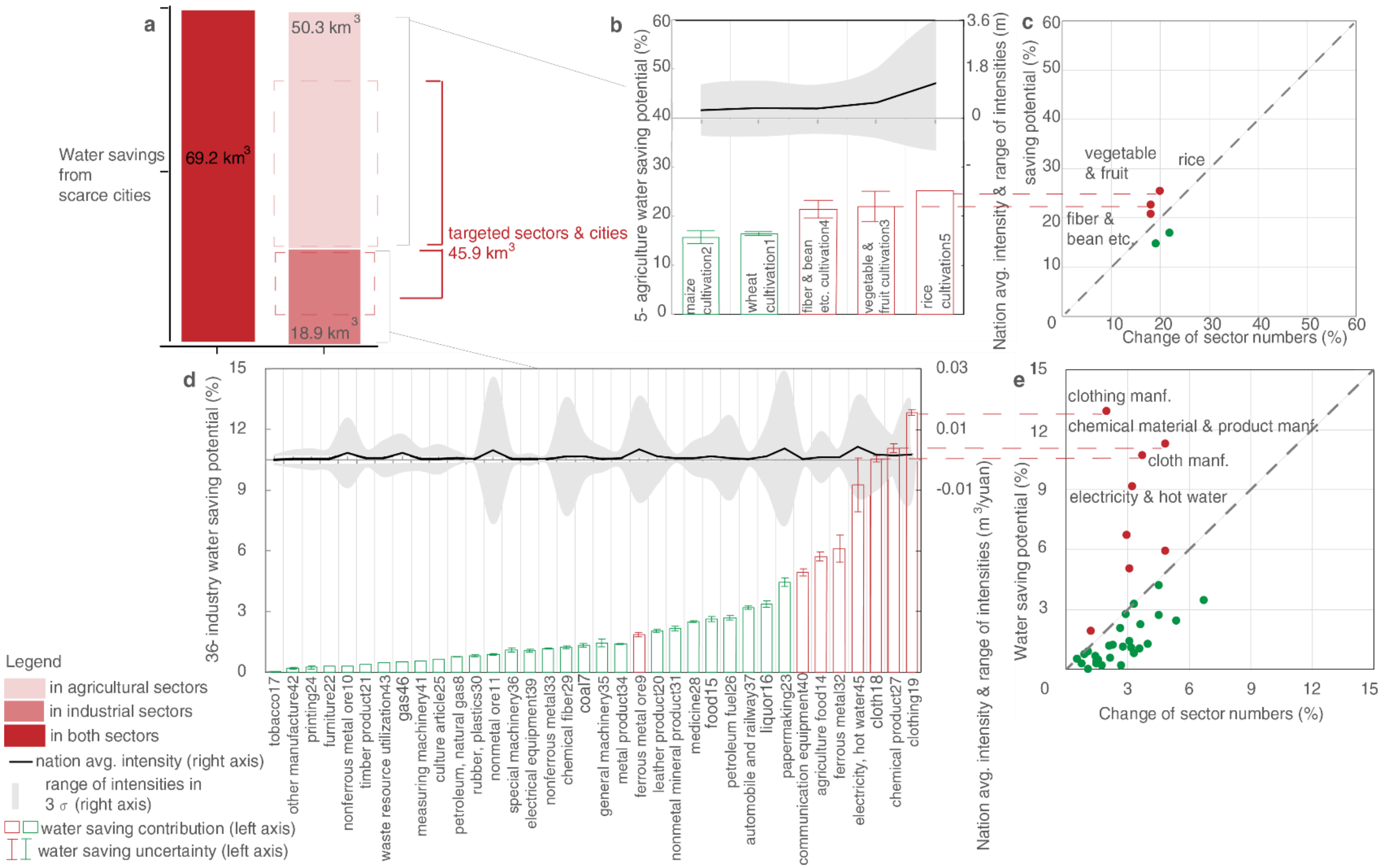

Figure 14 Water saving potential and withdrawal intensity (national average) in each of agricultural and industrial sectors

Note: In water scarce cities, (b) and (c) were in agricultural sectors, (d) and (e) in industrial related sectors. A few sectors were large contributors (in red, above the dotted line of 6-1(c) and (e)), whilst it was less effective to tap saving potential for most sectors in green (below the dotted line).

6.2.3. Implication for alleviating water stress

Together with agriculture, criticality-ratio reduction ranged from 0.24% in Harbin to 499% in Yinchuan at identical water availability levels. 18 cities would be alleviated below the scarcity threshold (40%) and shake off water scarcity, for example Xining, Zhangye, Hotan, Haidong (northwest), Jincheng, Yulin (west), Jilin city (northeast), Wuxi and Xiangtan (mid-east). Population of these cities amounted to 40 million (equating to national and total population of South Africa, or two thirds of UK population in 2021) (Phillis et al. 2017) and GDP accounted for 5% of China in 2015.

At the national level, although the situation would remain severe, mean scarcity level of water-scarce cities would fall by 20 percentage points from 96% to 76%, being alleviated to sub extreme-scarcity level.

6.3. Sectoral water saving strategies

Through unique account, I proposed that sectoral water saving should be well placed to alleviate water stress, by improving sectoral water-use efficiency, especially by reducing sectoral water-withdrawal intensities with a little cost to economy. I think sectors of low efficiency in water scarce cities should be well-targeted. Requiring all sectors to evenly or in-general improve water efficiency does not represent an optimal policy choice.

6.3.1. Sectoral water saving recommendations

I recommend water saving potential in a handful of sectors, i. e., 25.7% in industrial sectors and 10% in agricultural sectors, as these sectors identified to contribute to 63% and 70% of water savings, respectively. Focusing on these sectors makes sense in terms of producing water saving returns, whilst minimizing potential economic disruption across the wider economic base. China may therefore target key sectors and cities in redline regulations, rather than requiring all industries and cities to be involved in water saving.

Our results help to enable targeted saving strategies and identify priorities, to facilitate more effective water regulation through optimizing efforts for improving efficiency.

6.3.2. Realizing feasible technical improvement

Of course, realization of water intensity reductions is likely to be different (Tillotson et al. 2014) from my rather crude scenario analyses; technologies, evapotranspirations, climate and species between sectors and cities vary (Xu et al. 2020; Hu et al. 2016; Jacobsen et al. 2012), and we must consider institutional as well as technical interventions.

In fact, China’s water saving potential in this regard is significant, with opportunities for farmlands, factories and enterprises to adopt or advance efficient water-use equipment from their respective sector in the global environment. For example, the main improvements I would recommend in industry are water recirculation in dyeing of cloth(ing) manufacturing (Niinimäki et al. 2020), chemical manufacturing, and power generation. For example, through wet tower, abstraction per kWh could be improved from 168 liters to 5 liters (Byers et al. 2014); in agriculture improvements are efficient-irrigation techniques applied in Tongliao city, which could save total irrigation amount with rice, vegetable and fruit cultivation (Wei et al. 2016; Shen et al. 2011). For example, techniques with the state of the art in China are as follows: Hengshui city is aimed to become a pilot city for water conservation in Dec. 2018, and it has broadly applied drip and spray irrigation in modern agriculture parks. There are two above-100,000- metric-ton desalination factories in Qingdao city, which represent cutting-edge technology for China. In addition, mulch planting and the integration of water into fertilizer have also been developed in the cities of Yantai and Qingdao city. For more information, see websites of China Daily (http://www.chinadaily.com.cn/a/201806/29/WS5b35d76ba3103349141dfc75.html) and the people's government of Hebei province (http://www.chinadaily.com.cn/m/hebei/2013-07/02/content_16853000.htm) in

References.

Figure 15 Photos of representative water saving techniques; water recirculation (left) and drip irrigation (right)

Alternatively, I would encourage sectoral water abstraction and use rights, and incentives such as trade and other subsidies for water-saving sectors and cities (Wang et al. 2015a) through water management contracts (Zhao and Liu 2019). Given the fact that the first pilot city of water market has been opened in Kaifeng city in 2015 to alleviate water scarcity, other practices beyond China, including *unlimited list of options* through united research in the United States, vertical farming (Al-Chalabi 2015), water neutral development (Van den Abeele et al. 2017), and water pricing with full cost recovery (National Research Council 1999; Massarutto 2007; Mitchell and McDonald 2015) could also be explored to balance water demand and water supply. Regularly updated indices for leading-edge farmlands and enterprises, and high water efficiency manufactured products should be promoted by water efficiency labels (Wang et al. 2015b) and national awards. Finally, online/real-time monitoring on water withdrawal of key sectors at the city level through roll-out of smart meters should be considered (Zeng et al. 2013). Smart meters are for online instant monitoring and timely water management. Smart meters are new and more expensive (currently not affordable to most users). But it is promising to be promoted by governments. To remove the high-price hurdle, governments may start from large state-owned enterprises firstly.

At last, at the enterprise level, along with the improved efficiency, not all change is detrimental to enterprises, in terms of increasing operational cost, due to scale effects. Water saving would bring economic benefits. In other words, some retrofits would reduce cost considering other expenses would be saved, such as automation and raw materials (taking up approximately 70%), which is the case monitored in some demonstration sites (Wei et al. 2016; Shen et al. 2011). Total cost is not yet determined and to be explored. Certainly, there are some other conservation strategies that could prove better, which need to be researched and assessed more fully to find out.

6.4. Integrated water saving strategies at the city-level through cluster analysis

Cluster analysis usually refers to magnitudes of a series of pre-provision indicators (or variables) for specific datasets (Ramaswami et al. 2018). In result, difference within a group would be significantly small, whilst relatively large between groups i.e., clusters represent variables with similar attributes (Eisen et al. 1999; Edwards and Cavalli-Sforza 1965). Beyond administrative or provincial territories, city-level studies (Guan et al. 2018; Wu et al. 2020) concerning resource use across industries have utilized Shan et al. methodology (Shan et al. 2018) to classify Chinese cities into different groups with a k-mean cluster analysis. I used a similar treatment, employing proportions of industrial output, and supplemented with an agriculture-based grouping, to Shan et al. method. In this study, groups were clustered in-advance. Then I observed sectors in each city group. The second part is somehow separated or independent from group clustering. For example, agriculture-based cities accounted for greater proportions of farming, forestry, animal husbandry, and fisheries in their GDP than other cities, for example, Tacheng city and Bayannur in the Inner Mongolia, where there is a biggest irrigation area called Hetao and over-half of dairy products in China were produced. Agriculture-based cities were more developed in irrigation and also had higher water use. Usually the larger the area is, the more water is used.

I think six groups represented different economic development stages by assuming a development time lag. For example, representatives of service-based cities were the so-called first-tier cities, including Beijing, Shanghai, Guangzhou, Shenzhen, as well as provincial capitals such as Wuhan and Nanjing. These were categorized as wealthy and industrialized economies, as demonstrated by average per capita GDP of 132,302 Yuan. This ranked 1^{st} in all six groups, and was more than twice that of energy production cities. Service-based cities were assumed to take leading position for industrialization process in all Chinese cities. Despite the different economic contributions, policy between cities would be similar towards industrializations and there should be path dependency among them, although they have their own preferences in development. *Figure 16* shows GDP statistics in six groups.

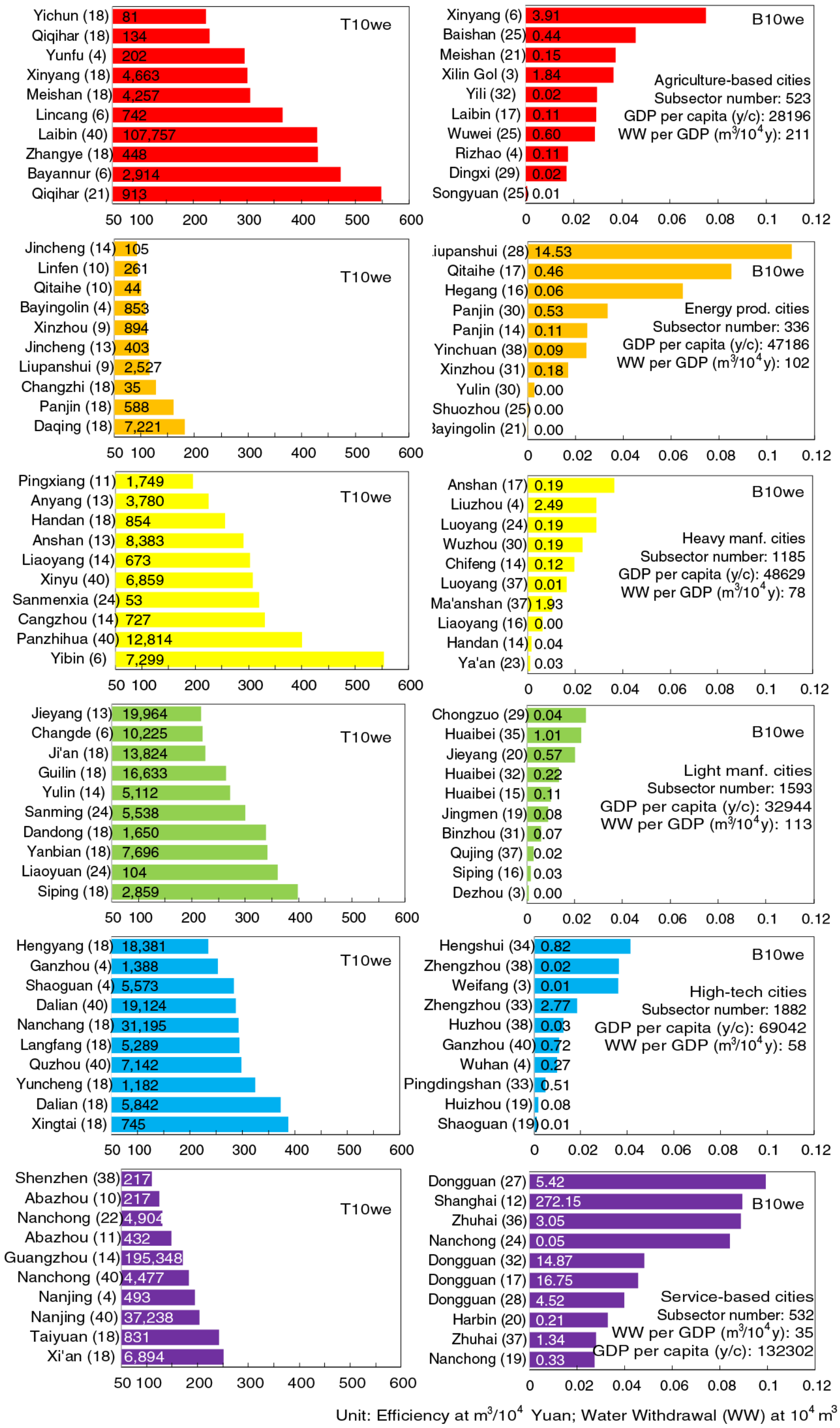

Figure 16 Top-/bottom-10 sectors for industrial water withdrawal efficiency (per output) and GDP statistics in each of six clusters

Note: T10we is short for Top-10 sectors for industrial water withdrawal efficiency, and B10we is short for Bottom-10 sectors for industrial water withdrawal efficiency. Sectors were represented with codes in the parentheses near y-axis. Number on each bar shows water withdrawal (WW) of individual sector. For average GDP per capita and water withdrawal per GDP, I calculated the sum of the numerator and denominator respectively before division.

Above all, *Figure 16* shows top-/bottom-ten sectors for industrial water withdrawal efficiency in six groups. Some low-efficiency and large water-users should be targeted to save water. Examples of energy production cities include Daqing, Panjin, Changzhi and Liupanshui. Although the top and bottom ten for water withdrawal intensity were amongst the smallest, this group appeared vulnerable since some cities such as Wuhai, Panjin, Hegang, Huozhou, and Qitaihe, have exhausted energy and water resources. High-tech cities followed, of which examples included Dalian, Nanchang, and Shaoguan. Water withdrawal were driven by modern industry, mainly manufacturing in Suzhou (south), Shanghai (east) and Jiaxing (southeast), for example, industrial parks in Suzhou. In heavy manufacturing cities, water withdrawal intensities were complex: these were amongst the largest, for example Panzhihua, Sanmenxia, Anshan and Handan, and most withdrawal efficiency varied across a large range. Service-based city water withdrawal intensities were not high. Furthermore, some cities were featured through cluster sectors with large water-use, such as Changchun (heavy manufacturing: special purpose machinery), Suzhou (high-tech manufacturing: communications equipment), and Yangzhou (heavy manufacturing: chemical materials and products). These sectors could learn from their peers within the same group.

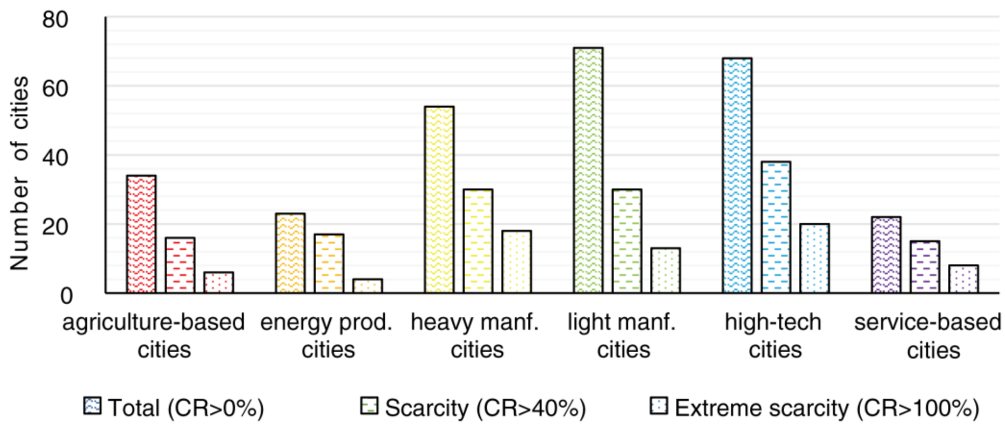

Figure 17 Statistics of city numbers in different criticality-ratio categories

Besides, I compared water scarcity occurrence amongst different city-groups. The most-severely affected were found in the high-tech group (Figure 17); 38 cities over the 40% criticality-ratio (water scarce) and 20 above 100% (extremely scarce). These are the highest in their corresponding tier, indicating economic growth limitations subject to water resources constraints. Notably, population in high-tech cities accounts for 33% of the total, and are commonly affected from severe water scarcity. For example, Bayannur is not sustainable in terms of water withdrawal: Unrenewable water resources would begin to decline, or water transfer projects should be much urgently needed. Heavy- and light- manufacturing cities were also ranked, behind high-tech cities.

I further found there appeared to be differences in criticality ratio in different city-types, indicating frequency and severity of water scarcity occurrence, referring to Veldkamp et al. (2016). For energy production cities (Figure 18), frequency seemed relatively higher, but not as severe when compared to heavy manufacturing group. Trendline curve peaked at 50%, exceeding the 40% definition for water scarcity. In other words, most cities appeared to be distributed to the right of scarcity threshold. Reassuringly, there appeared to be relatively few instances of cities occurring in the extreme scarcity region (i.e., >100%). In contrast, heavy manufacturing cities had lower frequencies of water scarcity occurrence, but once over the 40% threshold it tended to be more severe. The peak in the frequency trendline appeared at approximately 10-15% i.e., most cities tended to be distributed in a narrow band to the left of scarcity threshold. However, there was a greater, more even spread of samples above the extreme scarcity threshold, with a slight frequency approximately 5% for each distance, so the trendline tended to decrease gradually. Examples were Shizuishan (962%, northwest), Baiyin (489%, northwest), Alashan (287%, northwest), Dongying (200%, east), Baotou (189%, north) and Tangshan (136%, north). This small subset (approximately 13%) of cities in this group mainly influenced the findings for water scarcity in heavy manufacturing cities.

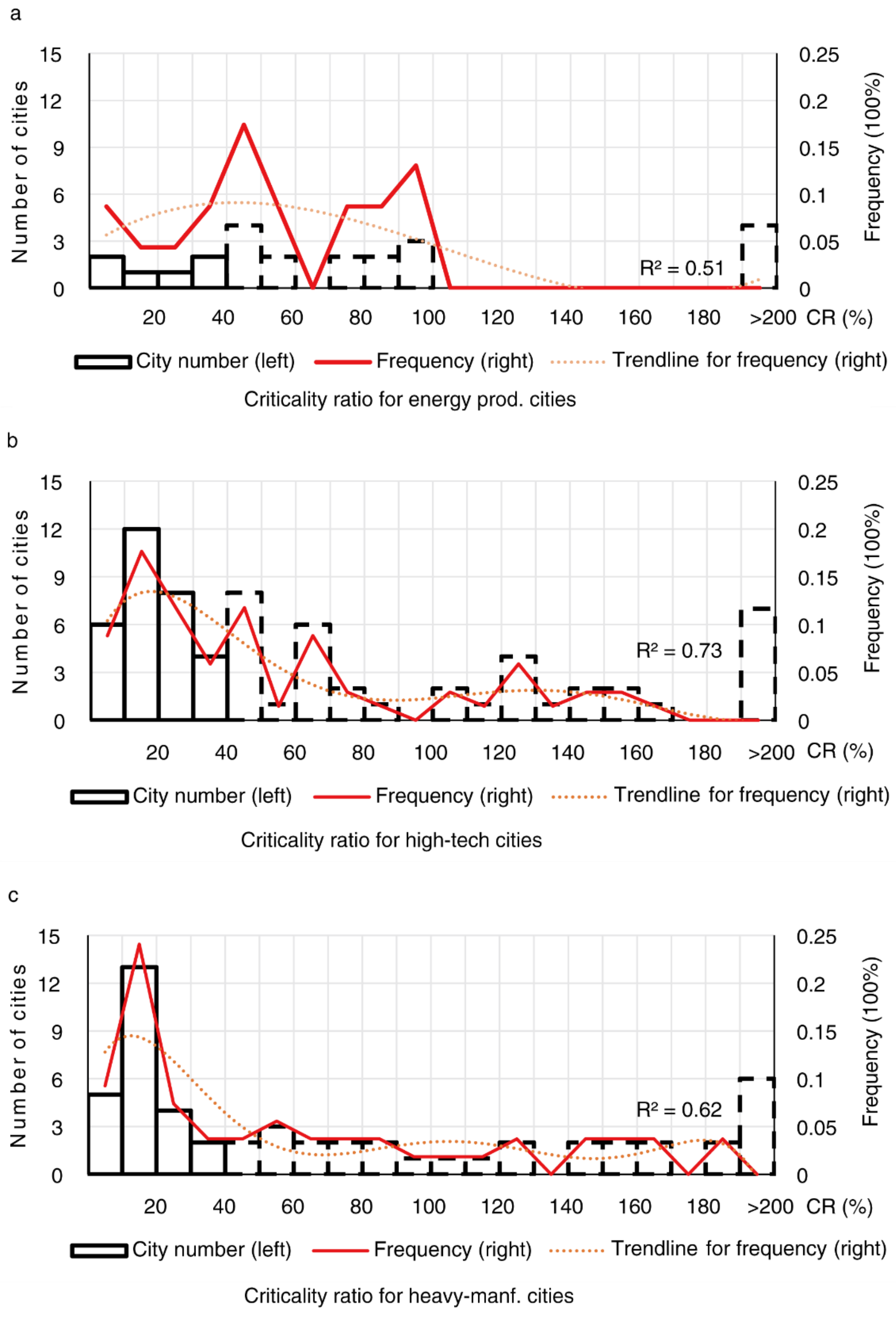

Figure 18 Histograms showing frequency distribution of the criticality-ratio for three representative city clusters i.e., energy production, high-tech and heavy manufacturing types

Note: Criticality ratios above the 40% threshold are indicated by dashed squares; I merged >200% samples due to slightly lower frequencies.

In sum, according to differences of scarcity occurrence in different city-types, I also considered distinct water saving strategies. For heavy manufacturing cities, policy focus should therefore be on a small number of scarce cities at this stage. By comparison, for energy production cities, policy makers should focus on a greater number of cities. For agriculture-based and light-manufacturing cities, given their relatively lower GDP per capita, balance between economic development and water saving needs to be better coordinated in decision-making.

6.5. Uncertainty analysis

I firstly conducted a sensitivity analysis on clustering. I clustered cities based on economic shares of GDP for primary, secondary and tertiary industries, then classified cities into three groups for sensitivity analysis. I found only minor differences between ratios of cities at individual water scarcity levels, from the groups using proportions of industrial output. Specifically, for agriculture-based cities, the >40% and >100% criticality ratios accounted for 46% and 17% respectively; for industry-based cities they were 54% and 25%; whilst for service-based cities they were 67% and 35%. Although clusters were based on different indexes, I found no substantial differences in water-scarcity distribution and status. I also verified water withdrawal per GDP of agriculture-based cities of 22 m^3 per 10^3 Yuan, which was close to the magnitude of representative agriculture province such as Heilongjiang at 21 in 2015 (Li et al. 2016). Finally, for individual city groups I validated median and average criticality-ratios and water intensities. In summary, verifications suggest the city clusters are unbiased, and the results are robust and credible.

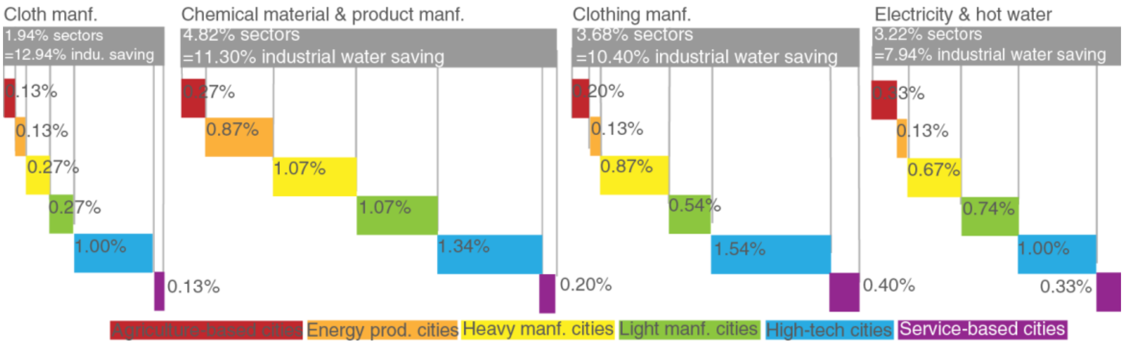

Figure 19 Top four water-saving industrial related sectors and their structure within different city-groups

What's more, water savings from cluster details also validate discussion on substitution. In scarce cities, industrial water savings would reach 7.90 km^3 for high-tech cities, 4.17 km^3 for heavy manufacturing cities, 3.40 km^3 for service-based cities, 2.71 km^3 for light manufacturing cities, 0.7 km^3 for energy production cities, and 0.62 km^3 for agriculture-based cities. Heavy-manufacturing cities would be alleviated by 11% on average to sub extreme-scarcity level (with water saving in industrial related sectors only). I also decomposed structure of top industrial sector-fraction into different cities and groups, and Figure 19 shows proportions of affected sectors from individual city-groups, respectively. Most severely scarce city-groups were effectively pinned down, such as high-tech, heavy- and light- manufacturing cities. These city-groups basically hold the top three places for efficiency improvements. For example, proportions of affected cities (sectors) in heavy-manufacturing and high-tech cities were all highest; 78% (37%) and 56% (26%) respectively. Thus, I was able to validate discussion reliably and robustly on substitution.

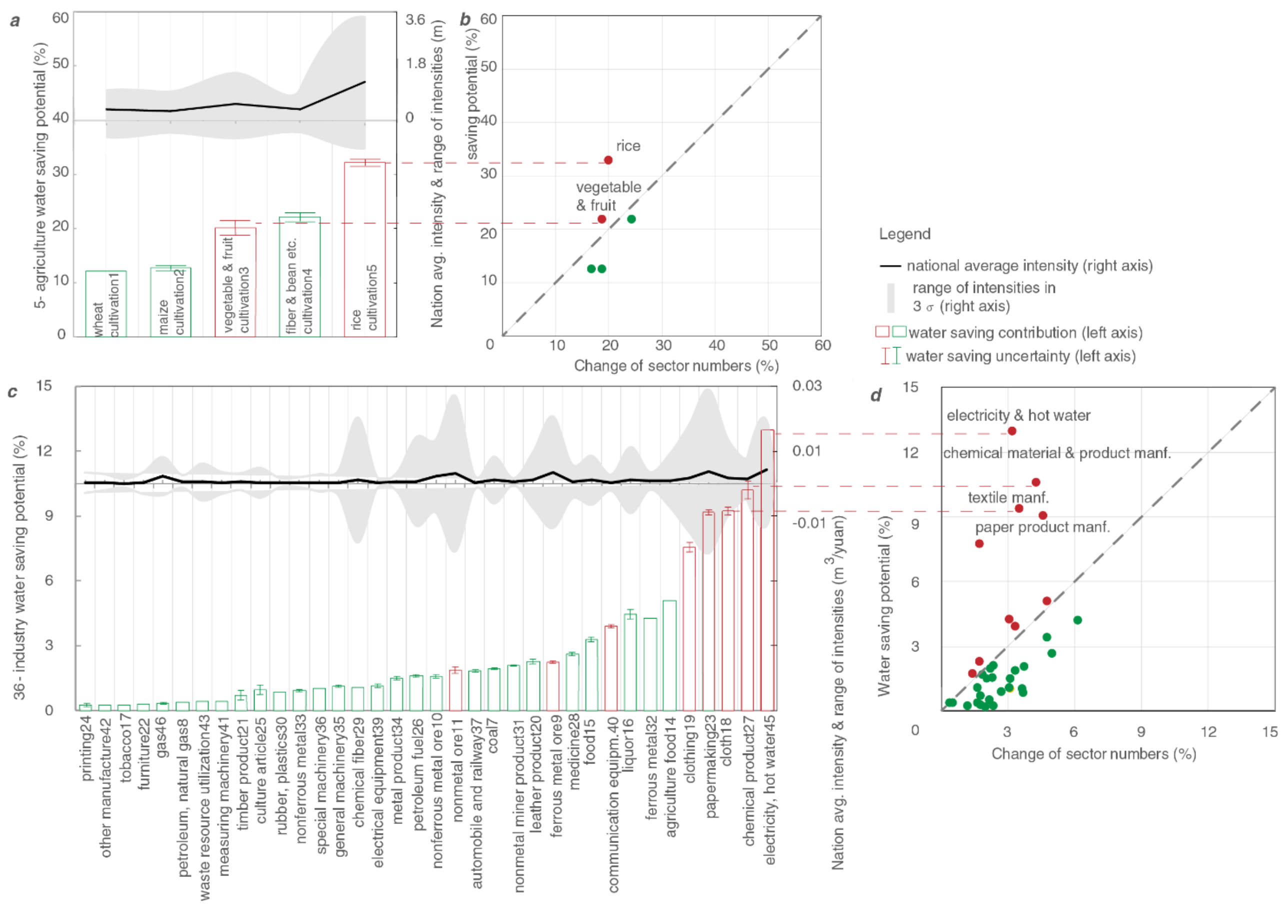

Figure 20 Water saving potential and withdrawal intensity in each of agricultural and industrial sectors in all cities
Note: In all cities, (a) and (b) were in agricultural sectors, (c) and (d) in industrial sectors. A few sectors were large contributors (in red, above the dotted line of (b) and (d)), whilst it was less effective to tap saving potential for most sectors in green (below the dotted line).

Finally, besides the efficiency substitution in water scarce-cities only, I assumed China would have water efficiency improvement in all cities and reported these results to enable a robustness check. In *Figure 20*, I estimated in industry 41.91 km^3 (±4.45%) water withdrawal could be saved. I compared this amount with total industrial water consumption amount (31 km^3) in 2015 and found this water saving for withdrawal was higher[23]. For Jing-Jin-Ji agglomeration 0.96 km^3 (±9.8%) water could be saved. In agriculture, 84.0 km^3 (±2.07%) water saving would be achieved.

6.6. Summary

To investigate sectoral water-saving potential and implication for alleviating stress, I built water-saving scenarios in 41 industrial and 5 agricultural sectors across 180 water-scarce cities, by assuming a convergence of below-average efficiencies to the national sector-average for technology improvement.

I found overall industrial water-withdrawal efficiency could improve by 20%, satisfying the redline regulation. 18.9 km^3 (±3.2%) water saving in industry and 50.3 km^3 (±2.3%) in agriculture would be achieved, equivalent to the annual water demand of Russia. A minority of sectors could contribute to most water savings whilst minimizing economic disruptions. In contrast, implementing water efficiency measures in the majority of sectors would result in significant economic change to achieve identical savings. As a result, water efficiency improvements should be targeted towards this minority of sectors: cloth(ing) and chemical manufacturing in industry, and rice, vegetables and fruits cultivation in agriculture. Through water saving, 18 cities would be alleviated below the scarcity threshold (40%) and shake off water scarcity. Population of these cities amounted to 40 million (equating to national and total

[23] Water saving here was about withdrawal and this comparison was with water consumption, not water withdrawal or water use. I compared this amount with total industrial water consumption amount (31 km^3) in 2015 and found this water saving for withdrawal was higher. Water savings amounted to 39% of total industrial water withdrawals (for all 272 cities).

population of South Africa, or two thirds of UK population in 2021) (Phillis et al. 2017) and GDP accounted for 5% of China in 2015.

Through unique account, I proposed that sectoral water saving should be well placed to alleviate water stress, by improving sectoral water-use efficiency, especially by reducing sectoral water-withdrawal intensities with a little cost to economy. I think sectors of low efficiency in water scarce cities should be well-targeted. Requiring all sectors to evenly or in-general improve water efficiency does not represent an optimal policy choice.

Our results help to enable targeted saving strategies and identify priorities, to facilitate more effective water regulation through optimizing efforts for improving efficiency. Water savings from cluster details validate discussion on substitution. Although I acknowledge the hypothesis on water-saving cost is a bit simple, I think it is valid and worthy of wider exploration. In summary, I anticipate this chapter will stimulate discussion and enable policy and technology interventions amongst industrial and agricultural sectors on water saving potential in China. I also think this research will generate wider academic and practitioner interest worldwide.

Given many facts, other initiatives may be not suitable for China (or too advanced) at the current stage. To target water saving measures by sector and location may optimize efforts for improving efficiency and should be simpler to facilitate more effective water regulation. China's water management has fallen behind and needed this improvement.

Chapter 7 Conclusions

7.1. Summary of methodological novelty for high-resolution water withdrawal accounting in China

I develop a general methodology for constructing a water withdrawal inventory across the sixty-three sectors for cities in China. This methodology features selection of 22 driving forces of water withdrawal. I connected each of 9 size indicators with its unique water-withdrawal efficiency, given different availability of water statistics collected from cities and provinces. The framework is the first to combine incongruent water-use data into one consolidated information set, for the first time in a developing country, drawing on the China High Resolution Emission Gridded Dataset (Cai et al. 2018) and previous water resources bulletins. In particular, industrial data across sectors were constructed based on water withdrawal efficiency, as benchmark performance, from a point-sourced survey for 343 prefectures and 41 industrial sectors in China (Cai et al. 2018; Zhang et al. 2020b).

This methodology applies to many different circumstances for water statistics in different cities and provinces and covers the principal water supply sources (including surface water and groundwater). Based on these sources, different sectors' water withdrawals are made consistent and form an open water inventory, which allows researchers to evaluate the quality of the current data and identify data gaps for future improvement.

7.2. Summary of results and key findings

7.2.1. Prefectural water withdrawal and stress accounts by sector and total

Applying the general framework, I accounted for water withdrawal of all 65 sectors (industrial and agricultural etc.), for all 343 prefectural cities for the first time in a developing country, using a 2015 data benchmark. Then I compared different scopes and methods of official accounts and statistics from various water withdrawal datasets.

I further accounted for total water availability, and water scarcity status in each of 343 prefectures. These datasets are transparent and verifiable. In sum, these high-resolution water accounts are unprecedented in China.

Through high-resolution water accounts, I identified cities suffering from water scarcity, and low water-efficiency sectors at the city level (compared with the national average). These sectors and cities should be well-targeted in sectoral water saving through efficiency improvement.

This may help planners obtain more accurate water statistics across the individual economic-social-environmental sectors driving water use and scarcity, which can help governments better regulate water resources in local activities.

7.2.2. Sectoral water saving in targeted cities

Through unique account, I proposed that sectoral water saving should be well placed to alleviate water stress, by improving sectoral water-use efficiency, especially by reducing sectoral water-withdrawal intensities with a little cost to economy. I think sectors of low efficiency in water scarce cities should be well-targeted. Requiring all sectors to evenly or in-general improve water efficiency does not represent an optimal policy choice. the results help to enable targeted saving strategies and identify priorities, to facilitate more effective water regulation through optimizing efforts for improving efficiency.

I first found agricultural and industrial sectors with high water-withdrawal intensity existed in representatively small developing cities. And the top 10% of low-efficiency industrial related sectors represent 46% industrial water withdrawal.

Then through scenario analysis across 180 water-scarce cities, I found overall industrial water-withdrawal efficiency could improve by 20%, satisfying the redline regulation. 18.9 km^3 (±3.2%) water saving in industry and 50.3 km^3 (±2.3%) in agriculture would be achieved, equivalent to the annual water demand of Russia. What's more, a minority of sectors could contribute to most water savings whilst minimizing economic disruptions. In contrast, implementing water efficiency measures in the majority of sectors would result in significant economic change to achieve identical savings. As a result, water efficiency improvements should be targeted towards this minority of sectors: cloth(ing) and chemical manufacturing in industry, and rice, vegetables and fruits cultivation in agriculture.

Notably, I took into account cost to economy, while targeting to specific sectors and cities for saving water. I recommended exploration of cost-effective and long-term saving options by considering disruptions caused to economy.

This complete analysis through unique account would bring a conceptual advance. These geo-data of high resolution would also facilitate proceeding to in-depth exploration. For example, data could be used directly in input-output models, consumption-based accounting and structural decomposition analyses to help gain in-depth insights, concerning allocating sectoral water withdrawal, and alleviating water stress from local activities. In sum, this primary research is an initial step to test knowledge limits and break through for China water science. I think this would appeal to the broad range of the community across the economic-activity base of 65 sectors.

7.3. Limitations and future research

I may have over-estimated criticality ratio, considering water withdrawal statistics do include those from reservoirs and upstream rivers, while water availability data do not include these parts. I was unable to incorporate these data into water availability generally due to statistical incongruence between cities. Similarly, for China's water availability research, there is a difference in terms of measuring water availability in the current literature: Due to data unavailability, most domestic research in China don't incorporate return flow (The Ministry of Water Resources 2019) while foreign (overseas) studies out of China include this part (National Research Council 1999; Hanasaki et al. 2012; Wada et al. 2014b). I assumed no water leakage or loss for transportation in this study (due to data unavailability in a large scale at the city level), yet there should be systematic leakage and substantial loss on most occasions. For example, in 2020 leakage rate from distribution pipelines by China's national and public supply was at approximately 10% (The Ministry of Water Resources 2019), and some others may be at approximately 30%. Thus, the results could suffer from an upward bias in some cities. In future, I will supplement these data by combining hydrological simulations (Veldkamp et al. 2016, 2015; Wada et al. 2011).

Besides, this study collated and accounted results for a single year and did not consider fluctuations in inter-annual precipitation and withdrawal (He et al. 2009; Wetterhall et al. 2012), due to data availability. Current datasets were only completed for a single year (2015) and did not consider interannual variability of water data. Specifically, there is water withdrawal variability in about 30% of all prefectures (Zhou et al. 2020) and it mainly influences northwest cities and those from middle (and lower) reaches of the Yangzi River. And I have observed significant fluctuation of water availability, for example a decrease of approximately 60% in Qingdao, Zaozhuang, Laiwu and Linyi cities in 2016, due to reduced precipitation in dry years (Yureklwe and Kurunc, 2006).

Water withdrawal may also be affected by variations in occasional hydrological disasters. For example, it is common for one city to use more water to combat drought, especially for the water used for agriculture and that for ecosystem and environment preservation, different from other resource data, such as energy consumption. This is an unneglectable characteristic of water accounting. Thus, sectoral water withdrawal may change by a large proportion even in adjacent or economically similar cities. These variations create high uncertainty in the estimations of the cities in question. In sum, variation of water availability for individual cities should be considered in future work. And I would like to work on time series datasets to address this limitation and further check the robustness of this methodology with data for 2008, 2010, 2012 and 2015, respectively.

I did not consider water amounts from water transfer projects, such as the South-to-North water diversion project in north China plain (Ye et al. 2021; Zhang et al. 2020a;

Feng et al. 2013). Data for the South-to-North water transfer is not readily available to the public, I could only get a few from the middle route of the South-to-North water transfer projects. This should be supplemented in future work. These further works will not only reduce uncertainty of water scarcity status, but also explore temporal insights into understanding of water scarcity and allow for more time-series and statistical-significance testing. Additionally, as precipitation usually displays a high level of spatial and temporal variability (Zhou and Yu, 2005; Yu et al., 2007), it would be meaningful to study the effects of precipitation on water use.

At this stage water quality-induced scarcity (Chaves and Kojiri 2007; Liu et al. 2017; Van Vliet et al. 2017) has not been included in this PhD-study due to lack of data for water temperature and salinity, nutrient and other pollutants. Besides, the extent to which water savings could be driven by water stress needs quantitative analysis. Additionally, in industrial sectors, it is better to use value-added to substitute output to assess efficiency, especially when such sectoral value-added data will be accessible in the future. For 2015 China High Resolution Emission Gridded Dataset, this survey may suffer from biases in the following two aspects: 1) Selection of sectors: for individual sector in each city, the survey has selected 12 enterprises on average; 2) Selection of enterprises: I may have under-estimated industrial water withdrawal intensity. The selected enterprises in provision should be large or 'excellent' enterprises. These large enterprises may have advanced technology and scale effect, thus intensity of these enterprises, as benchmark performance on water withdrawal efficiency, would be lower than medium- and small- sized enterprises. If I regard the large enterprises representing their whole sector, I would have under-estimated industrial water withdrawal intensity in the sector.

Although I searched for the most solid estimation methods based on the available bulletins and statistics, there are still some limitations to this study due to the defects in the sectoral figures. First, there is some potential to improve the water-use inventory when more disaggregated parameters are accessible, such as water withdrawal per floor space of housing completed, irrigation water withdrawal per area of green land in urban areas, water withdrawal per environment and sanitation area, and representative water withdrawal for accommodation and catering and for other services. This methodology does not solve all problems; instead, it delivers an essential tool for addressing these issues.

I only considered direct water savings for isolated sectors, and ignored coordination and synergy among sectors (Bazilian et al. 2011; Hoff 2011; Newell et al. 2019). It is not wholly feasible to assume a smooth knowledge transfer of water efficiency experience from wealthier cities to poorer ones, for example technology progress for saving water. On one hand, conclusion of this study could be partial because it is only from a sectoral water usage perspective. It also sill needs wider exploration about how many intensities of key and specific techniques I recommended are on earth, and how to promote and match them (one by one) in the real world. On the other hand, I would seek to communicate with Ministry of Water Resources and Ministry of Ecology and Environment based on this study. This is aimed to facilitate a survey on measuring, monitoring and addressing the problem. This study should reflect more on actions to take. Using 'number of sectors' as a proxy for the cost of sectoral water saving strategy should be only one of the many possible patterns or ways. Consumption-based water accounting considers water saving throughout the entire supply chains (Munoz Castillo et al. 2019; Bellezoni et al. 2018; Mi et al. 2016), which would be practical in future work.

At last, at the enterprise level, along with the improved efficiency, not all change is detrimental to enterprises, in terms of increasing operational cost, due to scale effects. Water saving would bring economic benefits. In other words, some retrofits would reduce cost considering other expenses would be saved, such as automation and raw materials (taking up approximately 70%), which is the case monitored in some demonstration sites (Wei et al. 2016; Shen et al. 2011). Total cost is not yet determined and to be explored. Certainly, there are some other conservation strategies that could prove better, which need to be researched and assessed more fully to find out.

Appendix tables and figures

I.

Table 12 A table of 65 sectors and their classifications used in this PhD study

Code	Full name and description	Classification
1	Wheat cultivation	Agriculture
2	Maize cultivation	Agriculture
3	Vegetables & fruits cultivation	Agriculture
4	Fiber and bean etc. cultivation	Agriculture
5	Rice cultivation	Agriculture
6	Forestry, animal husbandry, and fishery	Agriculture
7	Coal mining & processing	Energy production industry
8	Extraction, mining & processing of petroleum & natural gas	Energy production industry
9	Ferrous metal ore mining & processing	Heavy industry
10	Nonferrous metal ore mining & processing	Heavy industry
11	Nonmetal ore mining & processing	Heavy industry
12	Mining supporting activity	Heavy industry
13	Other mineral mining & processing	Heavy industry
14	Processing of food from agricultural product	Light industry
15	Food manufacturing	Light industry
16	Liquor, beverage, & refined tea manufacturing	Light industry
17	Tobacco manufacturing	Light industry
18	Cloth manufacturing (textile)	Light industry
19	Clothing manufacturing (apparel, footwear & hats)	Light industry
20	Leather, fur, feather, & related product & footwear manufacturing	Light industry
21	Processing of timber, wood, bamboo, rattan, palm, & straw product	Light industry
22	Furniture manufacturing	Light industry
23	Papermaking & paper product manufacturing	Light industry
24	Printing, reproduction of recording media	Light industry
25	Culture, education, handicraft, fine art, sport & entertainment article manufacturing	Light industry
26	Processing of petroleum, coking, & nuclear fuel	Energy production industry
27	Chemical material & product manufacturing	Heavy industry
28	Medicine manufacturing	Light industry
29	Chemical fiber manufacturing	Heavy industry

30	Rubber & plastics manufacturing	Heavy industry
31	Nonmetallic mineral product manufacturing	Heavy industry
32	Smelting & pressing of ferrous metal	Heavy industry
33	Smelting & pressing of nonferrous metal	Heavy industry
34	Metal product manufacturing	Heavy industry
35	General purpose machinery manufacturing	Heavy industry
36	Special purpose machinery manufacturing	Heavy industry
37	Automobile manufacturing	Heavy industry
38	Railway, ship, aerospace & other transportation equipment manufacturing	Heavy industry
39	Electrical machinery & equipment manufacturing	High-tech industry
40	Communication equipment, computer, & other electronic equipment manufacturing	High-tech industry
41	Measuring instrument & machinery for cultural activity & office work manufacturing	High-tech industry
42	Other manufacturing	High-tech industry
43	Comprehensive utilization of waste resource	High-tech industry
44	Repair of metal product, machinery & equipment	High-tech industry
45	Production & supply of electricity & hot water	Energy production industry
46	Production & supply of gas	Energy production industry
47	Production & supply of tap water	Energy production industry
48	Construction	Construction
49	Wholesale, retail trade	Service
50	Transportation, warehousing, and postal industry	Service
51	Accommodation and catering industry	Service
52	Information transfer, computer service, and software industry	Service
53	Financial industry	Service
54	Real estate	Service
55	Leasing and business services	Service
56	Scientific research and technical services	Service
57	Water, environment, and public facilities management	Service
58	Resident services and other services	Service
59	Education	Service
60	Health and social work	Service
61	Culture, sports, and entertainment	Service
62	Public management, social security, and social welfare	Service
63	Urban	Household
64	Rural	Household
65	Environment and ecology	Environment and ecology

II. A list of 20 cities used to calculate the water withdraw per service employee from the cities with statistical information at the national level:

Xiamen;

Shenzhen;

Zhengzhou;

Qingdao, Laiwu;

Lianyungang, Huai'an;

Wuhan, Huangshi, Shiyan, Yichang, Xiangyang, Ezhou, Jingmen, Xiaogan, Jingzhou, Huanggang, Xianning, Suizhou, and Qianjiang.

III.

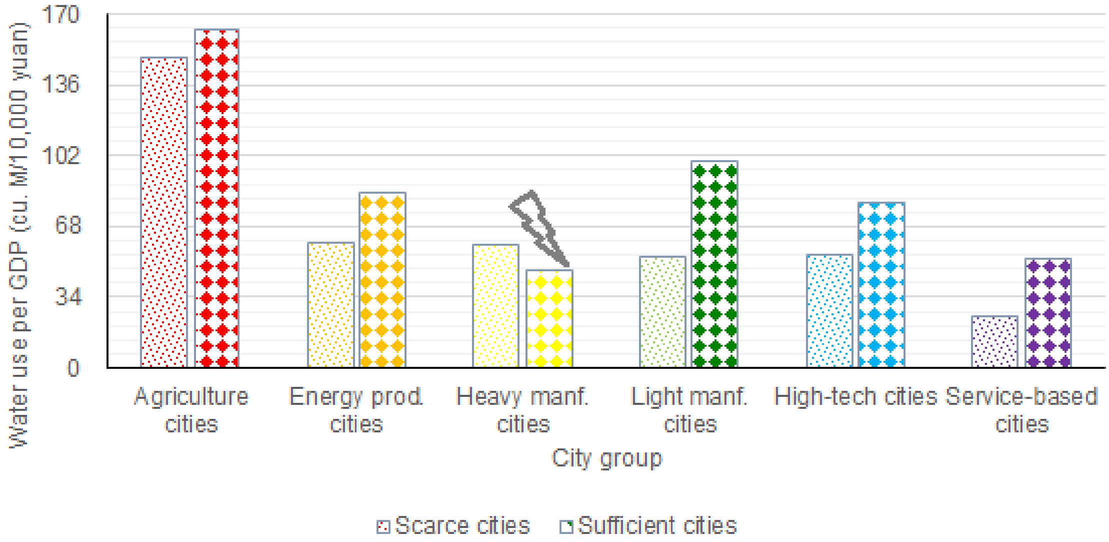

Figure 21 A comparison between water withdrawal intensities of scarce vs. sufficient cities in six groups

Note: the sigh of 'black flash' means a shock or alert for heavy-manufacturing cities because only this group is different from other groups. One might expect industries in water scarce cities to adopt water saving technologies, hence their water withdrawal intensities should be lower than comparable industries in water sufficient areas. In other words, water scarcity should force local industries to be front-runners in water use efficiency improvements. Unlike this hypothesis, I found that a few water scarce cities of heavy-manufacturing group (Figure 12(a)) such as Qiqihar (north), Yingkou (east), Wuhai (west) and Puyang (central), had water intensities much higher than in cities abundant in water resources. Although China has set intensity reduction redlines since 2011, reducing intensities of sectors in water-scarce cities should therefore be prioritized. Cities such as Wuhai, Hegang, Puyang, and Qitaihe, had water intensities which were still high, and they were not known to be over-exploiting resources until 2018 (Wang et al. 2019). Thus, awareness of sectoral water savings should be given greater focus in water scarce cities to prevent the situation to get worse.

IV.

Table 13 A table for boundary change of city in ArcGIS shapefile data of China's prefectures, compared to Zhou et al. (2020) and others.

No.	Code of city	Original	Corrected
1	B16	Pingliang (city)	Baiyin
2	B46	Yunlong (county)	Dali
3	B50	Tahe (county)	Tahe & Great Khingan
4	B85	Haikou (city)	Haikou, Sanya & Danzhou
5	B160	Heshan (city)	Liuzhou
6	B166	Zunyi (city)	Luzhou
7	B264	Changzhou (city)	Wuxi
8	B295	Mudanjiang (city)	Yanbian
9	B306	Wuzhong (city)	Yinchuan
10	B331	Wuzhong (city)	Zhongwei
11	B333	Daishan (county)	Zhoushan
12	B334	Chaohu (city), Hefei (city), Ma'anshan (city)	Hefei
13	B335	Jiangmen (city)	Zhuhai
14	B336	Guyuan (city)	Pingliang

Note: ArcMap 10.3.1 version was used. The same coordinate system was applied to all 343 cities.

V.

Table 14 An index of statistical description of six groups in this PhD study

Statistic item		Agriculture -based cities	Energy prod. cities	Heavy manf. cities	Light manf. cities	High-tech cities	Service-based cities	Total
City number of	total	34	23	54	71	68	22	272
	scarcity	16	17	30	30	38	15	146
	extreme scarcity	6	4	18	13	20	8	69
GDP per capita (y/c)		28196	47186	48629	32944	69042	132302	/
Water withdrawal per GDP ($m^3/10^4$ yuan)		211	102	78	113	58	35	/

VI.

Table 15 Water withdrawal and socioeconomic index of 18 representative cities in 2012

City	Water use (10^8 m^3)	GDP per capita (yuan)	Population (10^4)	Water use per capita (m^3/ capita/yr)	Water intensity (m^3/ yuan)	Annual household water use per capita (m^3/ resident/yr)
Hengshui	15.8	23033	442	356.8	68466.1	17.4
Yantai	12.1	75792	651	186.2	15991.0	22.1
Xi'an*	16.5	51086	793	207.3	32212.5	15.5
Chongqing*	82.9	39256	2945	282.0	211269.8	/
Tangshan	21.8	39256	342	635.0	55405.7	75.0
Xuzhou	10.0	41165	983	101.7	24292.6	9.6
Yangzhou	38.3	63985	458	835.0	59857.3	50.3
Shaoxing	19.0	56650	440	430.9	33498.0	57.2
Taizhou	19.2	48748	588	319.3	39338.7	44.7
Xinyang	18.0	23064	610	160.0	78042.5	/
Kaifeng	17.3	25921	610	273.0	66649.2	/
Luoyang	14.8	45699	656	224.0	32342.1	/
Anyang	13.8	31337	591	272.3	44167.2	24.6
Anqing	29.1	25601	619	518.2	11351.5	34.7
Bengbu	16.0	28135	366	493.7	56797.9	35.7
Tangshan	27.9	76437	739	377.5	36517.6	24.8
Zhangjiakou	13.0	28074	467	278.4	46395.8	20.6
Chengde	12.2	33708	375	323.6	36055.9	28.5
Qinhuangdao	7.7	37707	290	266.6	20535.0	14.9

Note: * indicates a capital city.

VII. Below is an initial version of accounting method based on above designated-size enterprises in China (ADSE). I took for example 13 cities in the north Beijing-Tianjin-Hebei urban agglomeration. This method was applied in Li et al. (2019) and methodology in Chapter 3 was in furtherance of this previous method.

For 3 centrally-administered municipalities, the Chinese Economic Census Yearbook provided the 2008 water use of 39 sectors. I calculate the 2008 water use structure of 39 sectors. Based on this structure, I allocated the 2012 gross industrial water withdrawal respectively to get the water use in each of the 39 sectors. There is a potential assumption that the structures of industrial water withdrawal of 39 sectors from 2008 to 2012 changed very little.

For Langfang and Cangzhou, there are no statistics of the industrial gross of ADSE but the whole sector

Based on this, I calculate the 2012 industrial water withdrawal of 39 sectors in the other 6 cities, containing Langfang, Cangzhou, Shijiazhuang, Handan, Baoding and Xingtai. I assume that the water use intensities of the same sector of different cities ε are equal to the water use intensity of the corresponding sector in the administering province (Hebei here). Because in the Economic Yearbook of Hebei province, data since 2009 have not covered the water withdraw from the sector of water production and supply. I use the average intensity in this sector of the 5 cities which did have these statistics to provide a supplement. Thus, for ADSE, $\varepsilon_{i,k}$=

$$\frac{\text{the industrial water use}_{i,k}}{\text{the industrial value added}_{i,k}} = \frac{\text{the industrial water use}_{j,k}}{\text{the industrial value added}_{j,k}} = \frac{\text{the industrial water use}_{P,k}}{\text{the industrial value added}_{P,k}},\ k \in [2,41] \quad (3)$$

To calculate the industrial water withdrawal of 39 sectors for the 6 cities who have no statistics, I calculate the industrial water withdrawal of 39 sectors with the industrial gross industrial output value of the ADSE in each sector as follows:

$$\text{the water use of ADSE in industry } k = \frac{\text{the industrial value added}_{P,k}}{\text{the industrial gross output}_{P,k}} \times \text{the industrial gross output}_{i,k} \times \frac{\text{the industrial water use}_{P,k}}{\text{the industrial value added}_{P,k}} = \frac{\text{the industrial water use}_{P,k}}{\text{the industrial gross output}_{P,k}} \times \text{the industrial gross output}_{i,k},\ k \in [2,41] \quad (4)$$

where I refer to Shan et al. (2017) to calculate the added value of ADSE based on the gross industrial output value of ADSE.

$$Water\ use\ of\ the\ whole\ industry_k = \frac{industrial\ water\ use\ of\ the\ ADSE_{P,k}}{industrial\ gross\ output\ of\ the\ ADSE_{P,k}} \times the\ industrial\ gross\ output\ of\ the\ whole\ sector_{i,k}$$

(8)

where the provincial data are sourced from the statistical yearbook of each province (In some provinces, it is called the Economic Yearbook or Development Yearbook of this province).

$$the\ industrial\ gross\ output\ of\ the\ whole\ sector_{i,k} = the\ industrial\ gross\ output\ of\ the\ ADSE_{i,k} \times \varDelta$$

In the beginning, these two methods used the same data source, the statistical yearbook. However, after a comparison between different sources and methods, I found the following:

1) Regarding household water use, the figures from the China city statistical yearbooks cover only the built-up districts, while the city water resource bulletins cover all built-up districts as well as county and rural areas. In this case, I regard the data from the city-level Water Resource Bulletin as a benchmark to obtain a consistent data source.

2) Some statistical yearbooks at the city level also provide sectoral industrial water withdrawal. Nevertheless, the data availability is too limited to support a sufficient analysis. For example, in 2012, there were as few as 59 cities in China that had sectoral industrial water withdrawal data. Moreover, the total industrial water withdrawal data exhibit significant discrepancies with the data provided in the Water Resource Bulletins. The possible reasons for this difference may be that a) the bulletin statistics incorporate the water use of enterprises below the designated size, while the yearbook statistics usually cover only enterprises above the designated size; b) the yearbook statistics include water use for external supply, while the bulletin statistics omit this information; and, last but not least, c) water withdrawal in the water production and supply sector is regarded as 0 in this study to avoid double accounting, considering that this sector is composed of tap water production and supply and sewage treatment sectors, of which the former transfers its water use to other sectors and the latter uses little water (Westerhoff et al. 2005). However, the statistical yearbook may double-count the water use in the water production and supply sector, and there is currently no method to extract this information.

3) Similarly, for yearbook statistics, since 2009, water withdrawal data have not incorporated cooling water directly from rivers, lakes, and seas, while bulletin data continue to include these. In addition, data from statistical yearbooks still suffer from being incomparable with data from previous years because the National Bureau of Statistics has adjusted the methods used to investigate industrial water withdrawal in terms of caliber and periods. Given these issues, using the yearbook values may cause inconsistency when combined with the other 5 sectors.

I ultimately substituted the statistical yearbook with the China High Resolution Emission Gridded Database and Water Resources Bulletins. All the comparisons above indicated that the results of this methodology are the most consistent based on the available statistical water data in China to date.

Based on these considerations, the data and methodology I presented here have gone through iterative verifications. The methodology in Li et al. (2019) was an early trial of the general methodology in this version: They differ in the selection of the driving force and the logic of sectoral congruence, and this methodology took into account different circumstances of data availability. Thus, the method here may have advanced the methodology based on more comprehensive knowledge of water statistics and accounting in China.

The updated version is based on water withdrawal efficiency, as benchmark performance, from point-sourced surveys in China in 2015. It features in selection of 22 driving forces, and I connect each size indicator with its unique water-withdrawal efficiency. The general framework is applied because only inconsistent water statistics collected from different data sources at the city level are available.

VIII.

Table 16 A table for view of criticality ratio, water availability, and total water withdrawal datasets (in partial cities)

City	Criticality ratio (100%)	Water availability (100 million m3)	Water withdrawal (100 million m3)
Anqing	21.88	123.52	27.02
Bozhou	48.13	22.25	10.71
Chuzhou	41.00	54.83	22.68
Huaibei	135.38	5.99	8.11
Huainan	229.98	9.94	22.86
Huangshan	2.25	149.35	3.36
Tongling	127.78	9.25	11.82
Wuzhong	1515.56	1.13	17.05
Yinchuan	1331.25	1.32	17.51
Bayannaoer	1105.90	4.58	50.65
Shizuishan	961.87	1.13	10.82
Kelamayi	929.99	0.65	6.06
Wuhai	910.34	0.29	2.64
Zhongwei	830.44	1.42	11.78
Jinchang	925.02	0.78	7.24
Lanzhou	685.51	1.83	12.52
Baiyin	488.95	1.94	9.48
Puyang	347.03	4.26	14.79
Qingdao	305.13	2.87	8.76
Alashan	287.25	3.53	10.14
Liaocheng	272.70	6.63	18.08
Hebi	219.82	2.28	5.01
Xianyang	207.26	5.37	11.13
Tianjin	200.27	12.82	25.68
Dongying	199.85	5.04	10.07
Zhengzhou	193.59	9.15	17.72
Baotou	188.97	5.62	10.62
Jiaozuo	181.83	7.51	13.66
Taiyuan	174.21	4.29	7.47
Jining	169.25	13.95	23.61
Anyang	161.93	8.87	14.36
Weinan	156.64	9.41	14.74
Wuwei	156.05	10.31	16.09
Dezhou	154.02	12.44	19.16
Zibo	151.87	7.04	10.69

Table 17 A table for view of sectoral water withdrawal datasets (in partial cities)

Unit: 10^4 m3 yr^{-1}	Jinan	Qingdao	Zibo	Zaozhuang	Dongying	Yantai	Weifang	Jining	Tai'an	Weihai	Rizhao	Laiwu	Linyi	Dezhou	Liaocheng	Binzhou	…
Farming, Forestry, Animal Husbandry, and Fishery	89075	24337	57658	29700	61490	56700	76500	184700	68270	23500	26000	10000	112000	162800	143600	128500	…
Farming irrigation total water withdrawal	72638	20040	49493	25500	52216	36000	69100	164300	58699	17100	22200	8800	90700	153200	133600	107800	…
Wheat cultivation	26594	6843	23151	7999	9862	12170	21632	49052	15421	5164	7720	1360	26782	58435	49828	42076	…
Maize cultivation	9964	2641	10136	2463	4434	6920	10905	15351	5906	2054	1638	1054	6475	20260	17543	13668	…
Vegetables & fruits cultivation	27307	7227	12396	12165	16263	9013	29513	63250	29070	4781	5195	5750	32377	39165	41442	32364	…
Fiber and bean etc. cultivation	5867	3326	3107	2608	19749	7887	7031	19482	8262	5101	5516	637	13692	35032	24508	18875	…
Rice cultivation	2906	3	704	265	1909	9	18	17165	39	0	2130	0	11373	308	280	817	…
Forestry, animal husbandry, and fishery	16437	4297	8165	4200	9274	20700	7400	20400	9571	6400	3800	1200	21300	9600	10000	20700	…
Industry	22696	19758	31655	11100	20064	12800	26900	22700	17649	7600	12500	9605	20500	14500	19000	9800	…
Coal	84	0	849	870	0	21	0	3703	4042	0	0	78	11	1	0	0	…
Extraction of Petroleum and Natural Gas	0	0	0	0	773	0	0	0	0	0	0	0	0	0	0	0	…
Ferrous Metal Ores	90	303	196	401	0	63	0	0	328	1	0	305	7	0	0	0	…
Nonferrous Metal Ores	0	0	0	0	0	588	0	9	0	28	5	0	14	0	0	5	…
Nonmetal Ores	0	62	117	0	0	0	55	0	61	0	0	0	919	0	0	0	…
Other Minerals	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	…

Processing of Food from Agricultural Products	963	2943	431	2299	713	1612	2443	4177	2903	4224	3193	2761	5721	2188	2085	471	…
Foods	1229	271	1099	83	424	207	1498	1188	181	404	396	56	1784	1388	3472	812	…
Liquor, Beverage, and Refined Tea	584	267	64	320	0	258	219	136	210	53	341	176	869	548	1202	32	…
Tobacco	21	0	0	0	0	0	0	0	0	0	0	0	57	0	0	0	…
Textile	865	1158	1526	983	2080	31	7791	181	612	49	120	8	952	1966	2005	1037	…
Textile Wearing Apparel and Caps	13	1575	150	772	0	2033	337	0	2083	84	0	0	1178	0	0	27	…
Leather, Fur, Feather, and Related Products and footwear	35	175	413	416	0	171	537	0	0	148	0	0	857	199	53	761	…
Processing of Timber, Wood, Bamboo, Rattan, Palm, and Straw Products	0	16	62	1	120	0	24	10	0	4	0	0	111	174	2144	1	…
Furniture	0	28	0	0	0	299	6	0	0	0	33	0	0	26	0	0	…
Paper and Paper Products	238	234	2373	1009	1219	1082	1755	1972	491	265	2610	344	1897	698	648	186	…
Printing, Reproduction of Recording Media	19	85	311	0	0	28	1	0	0	0	0	0	3	0	102	0	…
Culture, Education, Handicraft, Fine Arts, Sports, and Entertainment Articles	0	307	0	0	31	0	0	0	0	28	2	0	234	0	0	1	…
Processing of Petroleum, Coking, and Nuclear Fuel	321	174	745	91	2205	4	221	434	68	0	733	0	58	106	57	185	…

Raw Chemical Materials and Products	3058	7611	12691	2086	8596	2361	3711	2608	2543	320	780	392	1487	2249	2142	2885	…
Medicines	624	79	463	41	120	106	407	1076	68	31	340	0	382	1000	160	325	…
Chemical Fibers	63	22	40	0	449	38	788	87	1	1	0	0	0	212	0	194	…
Rubber and Plastics	47	429	157	19	1148	328	482	144	80	243	0	7	293	29	925	23	…
Nonmetallic Mineral Products	777	430	2964	482	386	400	204	497	406	83	205	5	551	134	124	28	…
Smelting and Pressing of Ferrous Metals	2193	371	620	0	0	73	910	16	427	40	2948	3023	91	308	896	57	…
Smelting and Pressing of Nonferrous Metals	11	345	1004	53	314	416	922	24	3	0	6	0	400	0	891	61	…
Metal Products	196	812	221	327	0	224	264	50	121	237	74	59	926	111	758	22	…
General Purpose Machinery	407	108	391	38	183	174	217	86	87	64	24	0	19	640	64	220	…
Special Purpose Machinery	316	168	310	0	0	58	99	242	1033	76	141	144	39	342	138	0	…
Automotive	462	74	0	0	0	103	0	48	0	32	0	0	0	9	0	8	…
Railway, ship, aerospace and other transportation equipment	0	70	0	0	0	0	0	0	0	85	0	0	0	16	0	0	…
Electrical Machinery and Equipment	50	670	510	43	0	183	372	50	160	100	65	0	10	1830	0	0	…
Communication Equipment, Computers, and Other Electronic Equipment	958	47	50	0	0	545	7	144	1	429	44	0	187	7	0	34	…

Measuring Instruments and Machinery for Cultural Activity and Office Work	10	39	3	106	0	11	0	0	80	3	0	0	0	0	0	0	…
Other Manufacture	2	23	5	0	0	0	0	1	35	0	0	0	79	44	12	0	…
Comprehensive Utilization of Waste Resources	0	13	0	0	0	192	1	0	0	0	0	0	10	8	0	0	…
Metal Products, Machinery and Equipment Repair	0		0	0	0	0	0	0	0		0	0	0		0	0	…
Electricity and Hot Water	9062	850	3889	659	1303	1191	3628	5817	1626	569	439	2246	1357	266	1123	2425	…
Gas	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	…
Tap Water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	…
Construction	1946	1953	569	870	797	786	2114	1170	2334	731	831	400	1904	238	615	213	…
Wholesale, Retail Trade	1248	960	92	164	283	224	461	262	112	263	269	115	499	135	161	79	…
Transportation, warehousing, and postal industry	541	876	36	101	117	289	269	164	672	183	418	119	215	69	193	47	…
Accommodation and Catering Industry	761	632	42	71	355	166	280	165	262	206	133	66	138	67	104	35	…
Information transfer, Computer Service, and Software Industry	980	166	11	20	81	59	120	36	296	39	36	20	80	21	32	17	…
Financial industry	908	670	52	86	199	183	190	311	316	156	147	58	243	77	288	53	…
Real estate	495	430	32	82	103	211	177	83	216	207	88	122	137	47	62	34	…

Leasing and Business Services	418	304	44	41	806	82	72	56	193	63	39	12	101	31	29	67	…
Scientific research and technical services	380	306	16	27	172	130	95	46	148	164	29	9	107	35	28	14	…
Water, environment, and public facilities management	169	229	28	59	86	84	440	64	82	138	31	13	129	32	61	15	…
Resident services and other services	34	109	3	11	17	9	8	9	47	18	2	14	17	9	4	6	…
Education	1238	1437	171	447	525	669	1084	638	1100	387	472	175	948	273	565	176	…
Health and social work	749	707	90	238	237	325	560	358	542	270	253	119	463	115	303	98	…
Culture, sports, and entertainment	194	130	19	16	20	39	30	26	40	23	22	5	32	8	26	9	…
Public Management, Social Security, and Social welfare	1146	1131	132	566	682	443	899	712	857	349	429	211	788	344	630	236	…
Urban and public	11207	10040	1337	2800	4481	3700	6800	4100	7215	3200	3200	1458	5800	1500	3100	1100	…
Construction	0	1298	0		0			0	0			98					…
Services	0	8742	0		0			0	0			1360					…
Urban Household	0	22757	0		0			0	0			0					…
Rural Household	0	4532	0		0			0	0			0					…
Household	23172	27289	12637	12800	9593	13700	18700	21200	15748	6000	7700	3095	26500	11800	13000	10400	…
Environment and Ecology	14383	6148	3631	4600	5096	0	5100	3400	6199	400	1700	329	7000	1000	2100	4200	…
Total water withdrawal	160533	87572	106918	61000	100724	86900	134000	236100	115081	40700	51100	24487	171800	191600	180800	154000	…
Productive water withdrawal	122978	54135	90650	43600	86035	73200	110200	211500	93134	34300	41700	21063	138300	178800	165700	139400	…

IX.

Figure 22 A national map of the study geographies used to indicate province and boundary

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Jointly-authored publications used in this thesis

Please see two jointly-authored publications used in this thesis, under PhD achievement list indicated by two footnotes (1/2 and 2/2).