

Supplementary Information

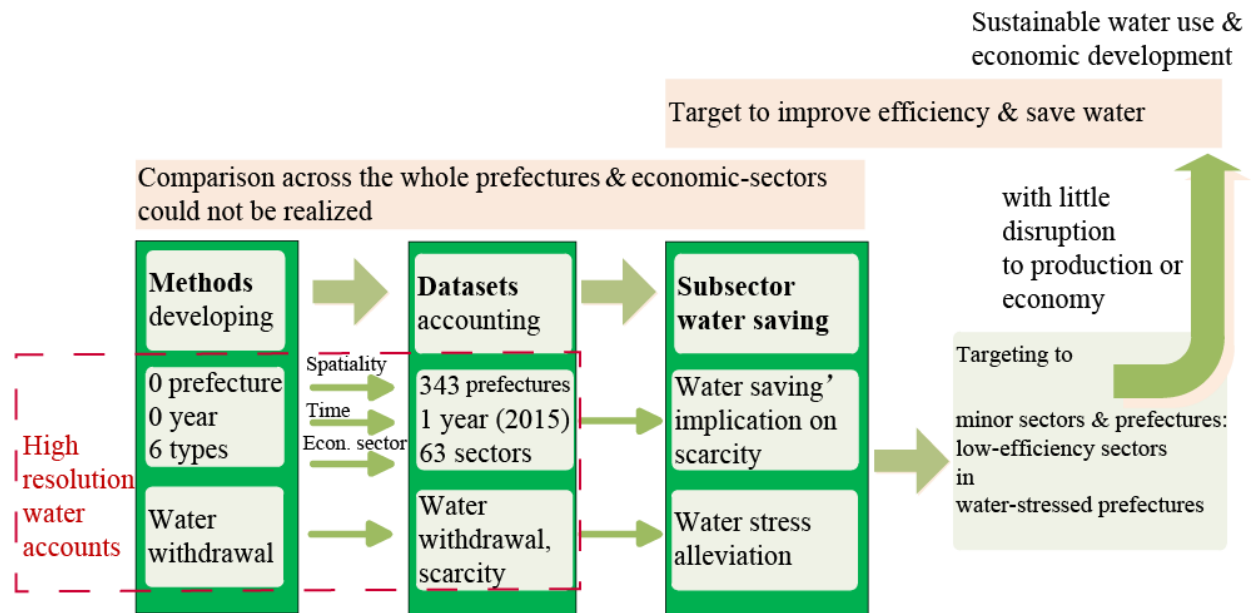
This PDF file includes:

Supplementary Figures 1 to 6;

Supplementary Tables 1 to 5;

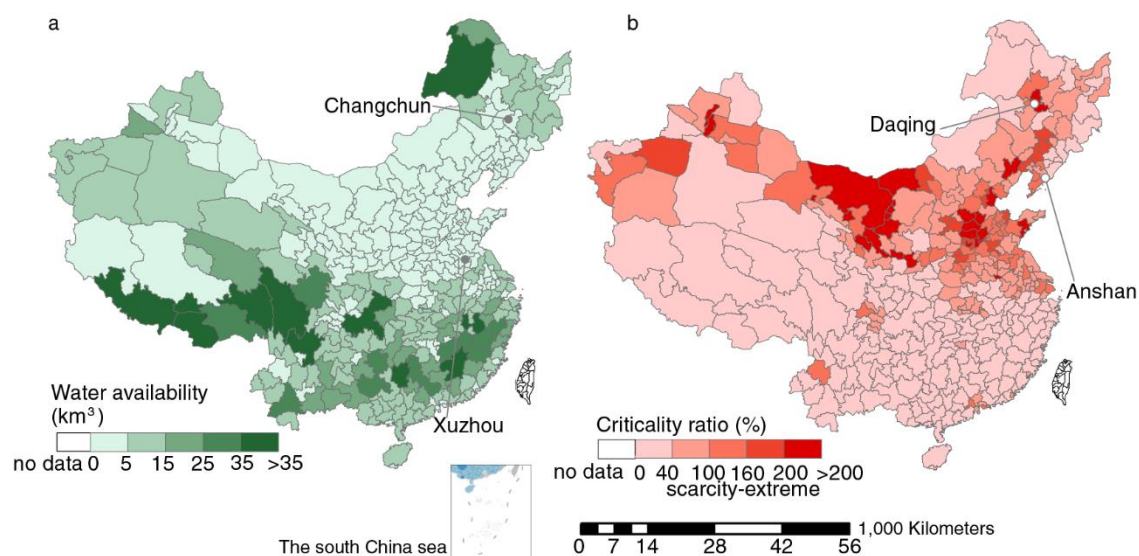
Supplementary Discussions 1 to 2;

Supplementary Methods 1.

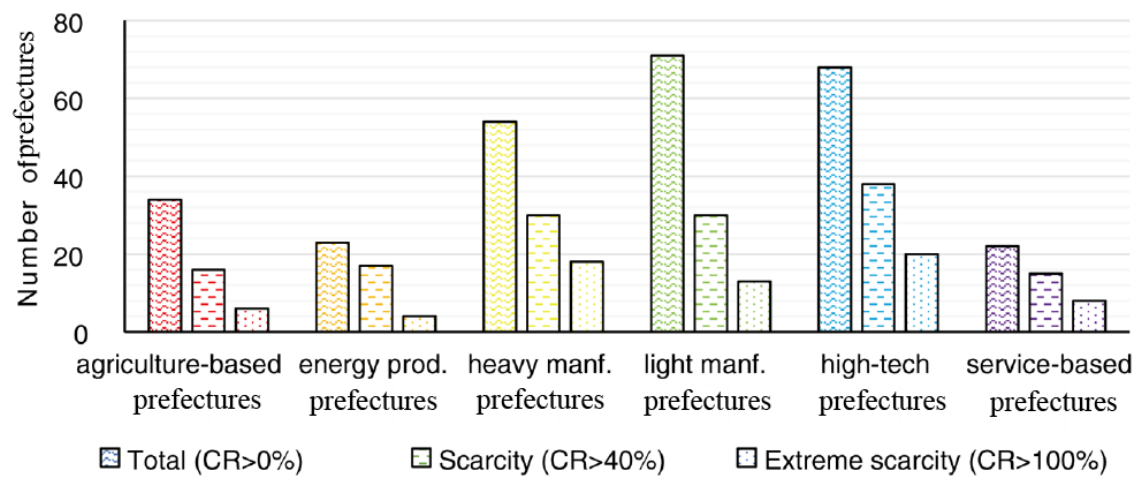


Supplementary Figure 1. Concepts and potential uses of high-resolution water datasets (DWUCs)

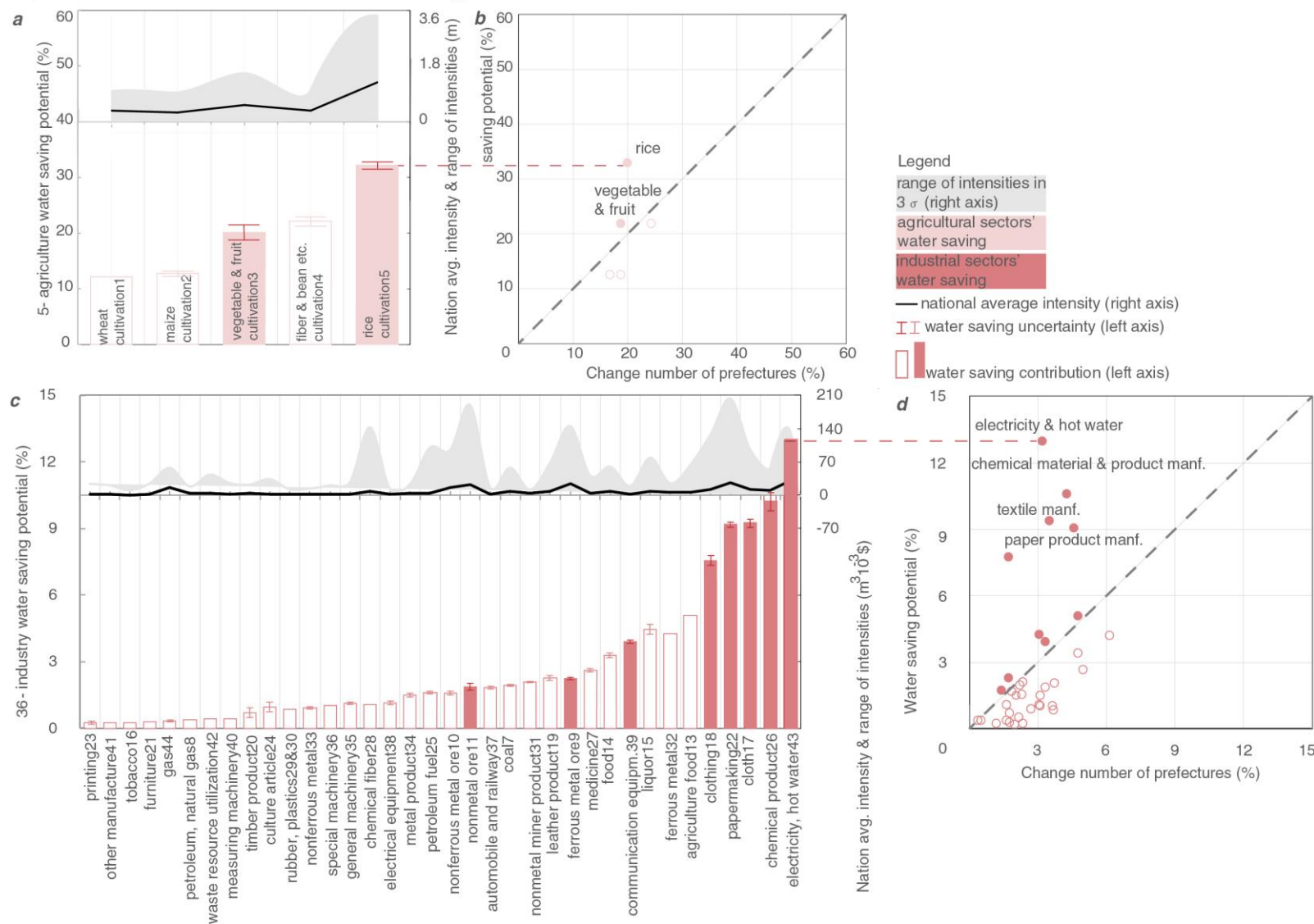
Basically, our research contributes in threefold: 1) high-resolution water withdrawal accounting methods, and accounts in terms of spatiality, time and economic-sector of China; 2) prefectural water-availability and -scarcity accounts of China; 3) subsector water-saving potential with targets on specific sectors and prefectures. These three parts could form a systematic research content.



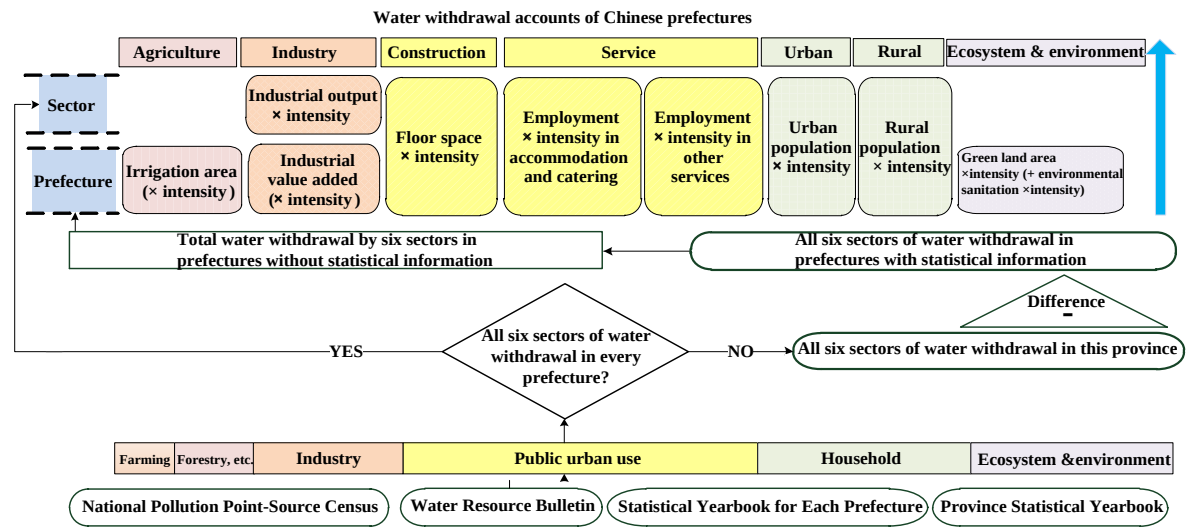
Supplementary Figure 2. Prefectures and their water-scarcity situation. (a) total water availability, and (b) criticality ratio. The average size of prefectures was 28 billion m², and average inhabitants were more than 4,430,000. Labeled prefectures are discussed in this study as they are characteristic in China. The figures illustrate an uneven distribution across prefectures, and are indicative of over-exploitation in some regions such as northern China. For example, several hotspots in northwest are Hotan, Korla and Bayannur, with criticality ratios exceeding 100%.



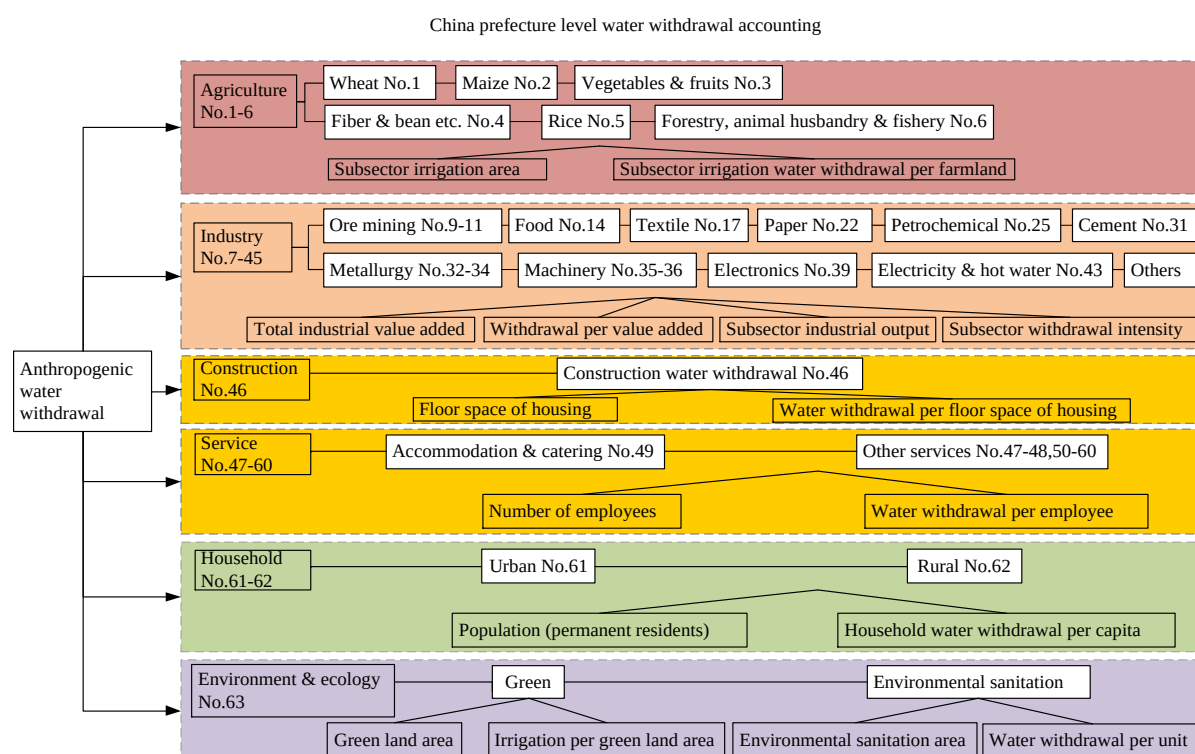
Supplementary Figure 3. Statistics showing the number of prefectures in different water stress categories.



Supplementary Figure 4. Water-saving potential and withdrawal intensity in each of agricultural and industrial sectors in all prefectures. (a) and (b) were in agricultural sectors, (c) and (d) in industrial sectors. A small number of sectors were large contributors (filled circles, and above the dotted lines in (b) and (d)), whilst it would be less effective to tap saving potential for most sectors (hollow circles, and below the dotted lines).



Supplementary Figure 5. A framework for subsector water withdrawal accounting at the prefecture level. The circled sources at the bottom indicate the primary data inputs used for estimation¹.



Supplementary Figure 6. Indicators for prefecture-level and subsector water-withdrawal accounting and classifications. It is based on selections of 16 driving forces for water withdrawal datasets.

Supplementary Table 1. List of 63 national economic-sector classifications used in our study

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

37	Automobile, railway, ship, aerospace & other transportation equipment manufacturing	Heavy sector
38	Electrical machinery & equipment manufacturing	High-tech sector
39	Communication equipment, computer & other electronic equipment manufacturing	High-tech sector
40	Measuring instrument & machinery for cultural activity & office work manufacturing	High-tech sector
41	Other manufacturing	High-tech sector
42	Comprehensive utilization of waste resource	High-tech sector
43	Production & supply of electricity & hot water	Energy production sector
44	Production & supply of gas	Energy production sector
45	Production & supply of tap water	Energy production sector
46	Construction	Construction sector
47	Wholesale, retail trade	Tertiary sector
48	Transportation, warehousing & postal	Tertiary sector
49	Accommodation & catering	Tertiary sector
50	Information transfer, computer service & software	Tertiary sector
51	Financial	Tertiary sector
52	Real estate	Tertiary sector
53	Leasing & business services	Tertiary sector
54	Scientific research & technical services	Tertiary sector
55	Water, environment & public facilities management	Tertiary sector
56	Resident services & other services	Tertiary sector
57	Education	Tertiary sector
58	Health & social work	Tertiary sector
59	Culture, sports & entertainment	Tertiary sector
60	Public management, social security & social welfare	Tertiary sector
61	Urban	Household
62	Rural	Household
63	Environment & ecology	Ecology

Notes: 1-5 are crop cultivation, 7-12 are associated with mining and processing, 13-42 are manufacturing, and 43-45 are production and supply of electricity, gas and hot water. These were selected according to the standard and widely-used classification of national accounting system, i.e., classification for national economic activities, released by the National Administration for Quality Supervision, Inspection and Quarantine^{2,3}. Full names of sector are indicated by & for short, throughout the paper.

Supplementary Table 2. Source data for Figure 4. Water reuse rate (%)

Prefecture	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	31	32	33	34	35	36	37	38	39	40	41	42	43	44
Beijing	45		90				85	4	30	27	4	0		0	8	59	3	12	100	98	74		89	86	97	97	75	49	55	78	2	90	4	13	22	94	
Tianjin		94			69		17	94	11	41	91	20	4	0	14	40	2	4	98	94	66	19	89	89	98	96	61	21	27	74	3	88	1	18	0	97	0
Shijiazhuang	91			55			16	37	17	92	27	14	29	22		39	64		96	92	91	61	40	97	97		4	54	41	16	13	11	0	7	0	98	
Tangshan	72	80	90	77			6	86	24		4	44		78	22	56	0		81	96	33	19	32	96	96	74	66	21	97	87	66	39		0	50	99	
Qinhuangdao			86				78	7	8		0	26			47	0			58	93	87	66		83	91	18	89	8	4	89	0	16	41	0	0	43	
Handan	74		78				34	61	41		68	0			21				90	91	14		19	85	96	0	93	13	19	0		0		74	16	98	
Xingtai	48		83		82		45	10	12		23	3	5		0	48	0	92	98	90	21	41	33	92	98	3	39	3	98	0	13	16	40	50	84	96	
Baoding			85	88	83		0	2	7	0	4	0	0	84		59	2		0	92	1	85	6	78	98	97	91	7	0	29	38	1	64	11		98	
Zhangjiakou	36		85	76	59		19	9	32	57	0	30			10				99	86	18		0	50	97	59	2	42	68	9	45		14		98		
Chengde	57		81	80	58		15	12	34		0	0	13		89				97	87	46		0	48	98	86	41	71	1	13	33				97		
Cangzhou		97					2	0	10		0	0	0	12	0	8		0	96	93	4	24	8	57	95	0	37	20	0	3	7	1		2		85	
Langfang							2	5	16		2	0	0	20	5	3	8	0	6	36	60		0	90	100	13	39	16	20	64	54	9		0		98	
Hengshui							10	42	28		4	9	16		20		29		91	34	12	31	32	90	72	5	0			55					99		
Rest of Hebei							44	2	1		35	3			45				97	96	16		13	86	96	56	0		33				0		99		
Taiyuan	84		92				1	17	8	93	33				47				97	29	89		20	72	97	69	0	67	88		16	51	80		94		
Datong	37		54	82	82		15	2	4			0	0		0				34	83	78		44	87	97	83	5	87	40	46	82		15	0	98	13	
Yangquan	79			0		0	0	60	30										99	25			23	74	0	85	89	0	41		36	96	0	0		80	
Changzhi	66		89				20	8	0				0		42	0	0		65	97	19		6	50	96	66	17	5	2	0	98	36			96		
Jincheng	44						14	6	10		23	2				0			51	97	0		53	85	38	43	56	41		20	1		0	8	98		
Shuozhou	53				43		14	5	6		0	17	0		6				34	5		53	26	45	9	0									46		
Jinzhong	86		54				0	51	12		0	0			0	83			85	92	6		96	71	50	72	71	2	5	0		0	10	0	83		
Yuncheng	60		65	85	10		1	13	16	6	14	70		49		25	80	40	59	97	22		75	35	78	90	70	51	31	53	17		71	51	91	0	
Xinzhou	63		96	84	40	49	17	20	35		5								96	19	79		0	22	56	93	47	86	72						25		
Linfen	54		70	79			1	1	6						92		33		95	96	7		43	92	92	82	90	94	94	33			96	98	82		
Lvliang	74		95	0			14	0	29						0				81	87	78		50	69	95	88	57	86	86		0		86	85	29		
Huhehaote			80	66			6	20	72	26	0	0			56				97	97	59	0		45	75	8	49		67		6		75		94		
Baotou			90	84	0		0	71	47		18				0				97	98	19		81	95	95	74	0	68	93						97		
Wuhai	78				0		0	95	11										91	94	0		97	96	91	77	43	20	0		0		0	9	97	61	
Chifeng	52	82	77	58	53		74	10	29		57	0	0			48	0		53	33	43		0	67	33	94	67	0	14					70	63	31	
Tongliao	7	6			0		33	84	18		0	0			33				95	61			94		86									67	96	25	
Ordos	40	49					1	90	17	0	1								91	94	35		42	95	87			0		44		0		90	0		
Hulunbuir	23	37	10	83	0		23	15	5					1	45				99	29			82		49	11							40		97		
Bayannur	93	100	65	91	30		2	16	17		1	6	0						94	44	6		14	9	91	61								99	56		
Ulanqab			83	79	46	0	16	3	2		0								0	90	4		98		84		6			0					97		
Xing'an	40			12			8	3	0	36	25								93	1			3	3					0			7		43			
Xilin Gol	75	77	78	90	2		1	1	0		0	0							16				85		44	49									89		
Alxa	51		62	90															60	41			30		67										61		
Shenyang	60	99	100				0	47	13	10	0	5	0	0	21	91	8	0	70	95	84	3	54	57	68	40	44	40	2	83	65	1	0	21		94	95
Dalian				0	79		21	14	29		0	0	0	0	0	0	0		50	81	84		25	92	99	0	93	6	11	1	45	3	0	0	0	41	17
Anshan	83		95		93		21	6	12		11	0		16	0	0			93	77	12		52	91	97	72	98	43	14	0	2		2			94	93
Fushun	80		13	78			8	13	0		9	13	3	25	47		24	0	98	98	1	96	34	70	98	89	32	63	13	0	95	0	42	32		96	
Benxi	92		88	52	30		2	0	7					0	0	0			89	96	7		0	52	95	1	21	76	0	46	90	0		70	92	0	
Dandong			79	58			0	2	0		3	0		0	0	32	0	8		57	0	63	11	33	80	51	1	51	0	27	0	0	2			93	93
Jinzhou	0	86			50		18	0	0		0	0	0		69				95	92	29	5	1	12	58	62	50	46		40	0	66	83	1		96	

Note: columns represent sectors.

Supplementary Table 3. An index of top sectors and prefectures with above-average water-saving potential.

Industrial or agricultural sector	Prefecture	Province	Industrial output (10 ⁶ \$) or Irrigated area (10 ⁶ m ²)	Water saving potential (10 ⁶ m ³)	Common characteristic, feature & similarity	
Cloth manufacturing	Guangzhou*	Guangdong	4,107	177	Mostly located in the east & south of China; into the subtropical monsoon climate zone.	Faced with common & hydrological challenges.
	Shantou		4,107	90		
	Zhongshan		2,494	61		
	Nanyang*	Henan	7,187	59		
	Pingdingshan		1,173	57		
	Huai'an	Jiangsu	4,401	109		
	Suzhou*		19,949	720		
	Anshan	Liaoning	1,614	79		
Chemical material & product manufacturing	Xiangyang	Hubei	5,574	89		
	Xiangtan	Hunan	1,907	224		
	Taizhou	Jiangsu	19,509	50		
	Tongliao	Inner Mongolia	2,787	59		
Electricity & hot water supply	Hefei	Anhui	5,867	51		
	Nanjing*	Jiangsu	2,787	294		
Rice cultivation	Huainan	Anhui	1,170	439	Agricultural practices in these prefectures often involve inefficient irrigation methods, leading to high water wastage.	
	Daqing	Heilongjiang	3,520	847		
	Baicheng	Jilin	2,510	403		
	Lianyungang	Jiangsu	3,030	454		
	Nanjing*		1,560	455		
	Nantong*		4,070	659		
	Suzhou*		1,240	427		
	Xuzhou*		5,430	693		
	Yancheng*		7,040	664		
	Yangzhou*		2,460	492		
Vegetable & fruit cultivation	Panjin	Liaoning	470	463		
	Chengdu*	Sichuan	2,150	765		
	Wuwei	Gansu	500	483		
	Bayannur	Inner Mongolia	170	4,436		
	Aksu	Xinjiang	6,200	1,335		
	Kashi		9,240	1,596		

* The highlighted are megacities with large population. These should be targeted in future water-saving policy interventions.

Supplementary Table 4 Source data for Figure 6.

Name	Agricultural irrigation intensity (withdrawal per irrigated area, 10^{-3} m^3 per m^2)		Industrial water withdrawal intensity (withdrawal per economic output, m^3 per 10^6 \$)	
	Before improvement	After improvement (°)	Before improvement	After improvement (°)
Tianjin	204	204	852	835
Beijing	381	N.A.	1499	N.A.
Nanjing	797	613	5804	1900
Xi'an	568	378	6086	1594
Chengdu	1084	N.A.	7117	N.A.
Shanghai	445	432	7391	2479
Wuhan	615	N.A.	8930	N.A.
Guangzhou	947	644	13455	4679
China carbon neutrality (2060)	1200		3194	
Global (2050)	741		25000	
Developing countries (2050)	763		30000	
Australia	563		4478	
Austria	178		9258	
Canada	560		35063	
Czechia	196		3667	
Denmark	198		329	
France	174		16722	
Germany	161		6846	
Greece	633		3956	
Hungary	625		27697	
Italy	573		5730	
Netherlands	87		12944	
New Zealand	434		12855	
Slovakia	75		2215	
Spain	608		7706	
Sweden	139		5426	
Switzerland	308		1586	
Near East/North Africa countries (2016)	753		853	

Note: N.A. denotes none-available data at the current stage.

Supplementary Table 5 Driving-force indicators and their sources.

Agriculture		Irrigation area	○	○ Province statistical yearbook △ City statistical yearbook ○/△ Province or prefecture statistical yearbook or internet search √ Water Resource Bulletins ※ National Pollution Source Census and Regular Reporting Systems of the Ministry of Ecology and Environment X the Bulletin of 1 st Water Resources Census (i. e., 2 nd Water Resources Census of Shanghai by the Shanghai Bureau of Statistics and Water Authority) U China City Statistical Yearbook
		Irrigation water withdrawal per mu of farmland	√	
Industry		Total industrial value-added	○/△	
		Water withdrawal per industrial value-added	√	
		Subsector industrial output	△	
		Disaggregated water withdrawal intensity of each sector	※	
Construction		Floor space of housing	○	
		Water withdrawal per floor space of housing	X	
Services	Accommodation & catering	Number of employees in accommodation & catering	U	
		Water withdrawal per employee in accommodation & catering	X	
	Other services	Number of employees	U	
		Water withdrawal per employee in other services	X	
Household	Rural	Rural population (permanent residents)	○	
		Household water withdrawal per capita in rural areas	○/△	
	Urban	Urban population (permanent residents)	○	
		Household water withdrawal per capita in urban areas	○/△	
Ecosystem & environment		Area of Green land	U	
		Irrigation volume per area of green land in urban areas	X	
		Environmental sanitation area	△	
		Water withdrawal per unit	X	

Note: municipal water-use statistic is not a routine indicator within China's own statistical calibres currently, and it should be commonly used in many countries except China. In China, it sometimes includes water-use for construction, service, and ecosystem and environmental preservation.¹

Supplementary Discussion 1 on water environmental-regulation in China.

To be brief, affluent coastal prefectures generally implement stricter water-use policies, while smaller inland prefectures adopt more lenient regulations to promote economic growth. These regulatory differences shape the distribution of water-intensive industries, which tend to cluster in inland areas where policies are more relaxed.

i.) With regard to the loose environmental-regulation or enforcement in different stages or periods of development^{4,5}, early studies Zhou et al. (2013) and Kuang et al. (2018) stated ecological regulations at detailed and different stages of an urban system⁶, including the famous Xiong'an New Area of Hebei province of China⁷. We also referred to Zhang et al. (2020)⁸ and Zhou et al. (2020)⁹. For different regions, Wang et al. (2019) and Wang et al. (2023) investigated distribution of irrigation regulations and techniques correspondingly^{10,11}. We also referred to Zhang et al. (2022)¹². These literatures show that inland regions are usually water-scarce but tend to loosen their regulations for economic development, due to crop cultivation and lower wealth per-capita. This could also result in relatively more water-intensive crops and heavy-industries being located in these inland prefectures. Specifically, loose regulations are in terms of evaluation for policies and plans, which are usually conducted or reflected by the inland authorities or local governments themselves.

Such differences from loose to stringent regulations bring industrial transfer and market restriction policy: introduction of technology and industries, and sales of products, should be based on how much water a local prefecture has, and whether their water efficiency performance could meet local standards, otherwise it should only be eliminated or transferred to somewhere with looser restriction^{8,13,14}. For example, some industries in Beijing have already been relocated into its surrounding provinces, in accordance with geographical endowment of water resources. This policy could be matched with water label policy.

ii.) Concerning water-use structure and industrial scenario analyses, there are also some other detailed and economic simulations through multi-objective optimization and decision-making models inter-cities^{12,15}. For example, Zhang et al. (2020) applied an Input-Output model to simulate and demonstrate that water-saving techniques are readily available and conducive in the process of industrial restructuring⁸.

Supplementary Discussion 2 on technology cost and water policy.

Given that improving water-use efficiency is a slow and difficult process¹⁶, at this stage, we find difficulty in obtaining or mapping our fined and detailed technical data as for each prefecture or sector¹⁷, i.e., specific techniques, accurate water-use amount for industrial output (\$) or agricultural crop (or irrigated area, in m²), water-saving coefficient and cost¹⁸. Concretely, 1) we could find techniques at the product and equipment levels, as Xu et al. (2024)¹⁹ did, to cut down package-related water use. Other studies are through material flow and metabolism analyses⁶, agent-based models¹⁸ and life cycle analyses¹⁹. 2) We could also find techniques typically within a certain sector¹⁸. In this regard, most research focus on cooling systems within the power-generation sector, or iron & steel sector²⁰. Yet we find challenge in matching technique information.

This challenge stems from existing water policies¹⁷, in particular control on water-use price. For example, in coal-fired and power-generation sector of China, there is no substantial difference on generation costs from the one-through cooling techniques to circulation cooling techniques. Moreover, water-related cost merely occupies a small proportion in the total generation costs at 0.05 US\$ per kwh^{21,22}. The water-related cost ranks after fuel cost (1st), investment depreciation cost (2nd), and operating and maintenance cost (3rd), as a previous study find that at current water prices, commercial companies are unlikely to adopt water-conservation measures²³. We would like to extend this part continuously in the future, as put in the reference¹⁷.

Supplementary Methods 1. Sensitivity analyses

We supplemented to perform sensitivity analyses as recommended.

For method validation, we referred to and used procedures in previous studies^{24,25}. Overall, for *Case 2* on estimation for prefectures without water withdrawal statistics, water withdrawal efficiency was a key uncertainty. We conducted sensitivity analyses by replacing these efficiency data with regional efficiency. The regional efficiency data were from provincial and regional Water Resources Bulletins.

Concretely, we estimate the sensitivity of water withdrawal by agriculture and industry for prefectures, by replacing the specific intensity value with regional, provincial or national magnitudes based on data availability. We take the prefectures 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 prefectures.

For agricultural water withdrawal, one assumption is applied for prefectures without statistical information: If there is no available irrigation water-withdrawal per mu for farmland, the water withdrawal intensity for the agriculture sector would be the same. We conduct a sensitivity analysis by replacing the intensity with the regional or provincial values, the results of which are shown below:

Supplementary Methods Table 1 Sensitivity analysis of agricultural water withdrawal

Prefecture	Original agricultural water withdrawal (10 ⁶ m ³)	Irrigation area (10 ³ hectare)	Irrigation water withdrawal (m ³) per mu for farmland	Replaced agricultural withdrawal for sensitivity test (10 ⁶ m ³)	Percentage difference (%)
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 $(\text{column2} - \text{column5}) \div \text{column2} * 100\%$. + and - are determined by whether actual intensity of selected sample is higher than the provincial average or not in their respective sector. Table 1 is for agriculture and Table 2 is for industry. Table 1 and Table 2 are somehow separated or independent from each other.

Although the largest differences between *Agricultural water withdrawal*' (estimated with the replaced agricultural water withdrawal intensity) and our original estimation appeared in Wuxi and Changzhou (-14.3%) in Table 1, the average variation of the absolute value was 9.0%. This result indicates that there are no substantial differences, and our method provides a credible estimation of agricultural water withdrawal.

Supplementary Methods Table 2 Sensitivity analysis of industrial water withdrawal

Prefecture	Original industrial water withdrawal (10^6 m^3)	Industrial value added (10^9 \$)	Industrial water withdrawal (m^3) per k \$ value-added	Replaced industrial withdrawal for sensitivity test (10^6 m^3)	Percentage difference (%)
Hefei	964	33	30.7	1011	-4.8
Bengbu	291	10	30.7	305	-4.8
Huaibei	214	7	30.7	225	-4.8
Tongling	185	6	30.7	194	-4.8
Huangshan	54	2	30.7	57	-4.8
Suzhou	157	5	30.7	165	-4.8
Xuancheng	176	6	30.7	184	-4.8
Wuxi	520	43	10.2	502	3.7
Xuzhou	477	40	12.3	552	-13.5
Changzhou	461	38	10.2	444	3.7
Nantong	511	43	9.5	467	9.5
Lianyungang	204	17	12.3	236	-13.5
Huai'an	261	22	12.3	302	-13.5
Zhenjiang	358	30	9.5	327	9.5
Taizhou	434	36	9.5	397	9.5

Note: For prefectures in Anhui, we could obtain only the industrial value-added for the above-designated-sized enterprises.

For the industrial water withdrawal estimation, although the largest differences between *Industrial water withdrawal*' (estimated with the replaced water withdrawal intensity) and our original estimation appeared in Xuzhou, Lianyungang, and Huai'an (-13.5%) in Table 2, the average variation in the absolute value was 7.3%. This result indicates that there is relatively low sensitivity, and the method provides a credible estimation of industrial water withdrawal. Moreover, the prefectures were the same as those selected for the validation of agricultural water withdrawal, which also supports the robustness of our method.

Supplementary References

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