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Water-saving strategies across prefectures should target the manufacturing and agriculture sectors in China

Check for updates

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Water scarcity is a global challenge in many emerging economies, including China. China is one of the most extensive freshwater users and has set water efficiency improvement goals for 2030 at the prefecture level. However, no systematic water use and savings comparison exists across prefectures and sectors. Here, we used datasets of water withdrawal for 10,608 industrial and 1715 agricultural sub-sectors for 343 prefectures, and explored the opportunities to reduce water use. Results show that 10% of the least water-efficient industrial sub-sectors represent a disproportionate 46% water use. 18.9 km³ ($\pm 3.2\%$) water saving in industry and 50.3 km³ ($\pm 2.3\%$) in agriculture could be achieved, equivalent to Russia's annual demand. A minority of sectors, including cloth(ing)- and chemical-manufacturing, rice-, vegetable- and fruit-cultivation, could contribute the most to water savings. Our study is essential for identifying water use and efficiency information for individual prefectures and sectors.

In the coming decades, climatic and societal changes, such as heat waves, precipitation variation and increased urbanization, are projected to exacerbate global water scarcity^{1–3}. By 2050, global and urban water use could surge by 80%, exacerbated by increased demand for energy and food, and the accompanying water pollution nexus. The two largest water consuming sectors are irrigation for agriculture (approximately 60%), and industry (approximately 25%)²; the agricultural share varies from approximately 40% in developed countries, to 60–90% in developing countries^{4,5}. By 2030, the UN Sustainable Development Goals propose universal access to safe and clean water (6.2.1, 6.4.1, 6.4.2)⁶. Meeting this goal relies on regional water-security, particularly in developing and emerging economies, such as China and India⁷, which contain the most populous megacities in the world^{7,8}. In 2022, amongst the top-20 largest cities by population size, five are located in China, three in India, and ten in other emerging economies. For saving water in megacities like Mumbai, Cape Town or Amsterdam, large-scale water restrictions and economic shut-downs between 2018 and 2022 captured global attention^{9,10}.

China consumes the largest amount of water in the world¹¹. The country is comprised of 343 prefectures, i.e., prefectures, the term used for

sub-provincial administrative units. China's water withdrawals for industrial and agricultural use have been at high and sustained levels over the last two decades: above 103 and 343 km³ yr⁻¹ by 2021, respectively¹². Average share of agricultural irrigation occupies approximately 60%; industrial water withdrawals are ranked the first in 17% of prefectures, and the first-two places in 97% of prefectures among productive water withdrawals^{13,14}. In an attempt to save water, the Chinese Government introduced water-saving ambition and redline regulations by 2030 under the Most Stringent Water Resources Management System¹⁵, and carbon-peaking commitment by 2030 and carbon-neutrality by 2060 for green development, meanwhile keeping GDP per capita to mid-level of developed countries by 2035. However, this is problematic in threefold, and there are no systematic and consistent comparisons of water efficiency indicators across all prefectures and economic sectors in China¹⁶. First, research is mainly limited to water use by the energy-related sectors and neglects many other water-consuming sectors, for example, water withdrawal inventories for construction of large coal-fired power generation hubs¹⁷; subsector and systematic water withdrawal datasets are not publicly available^{16,18} (here a sector denotes at the national level, 63 broad classifications, as is shown in Supplementary

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Table 1. This is defined according to the latest national accounting system for economic activities, which can be concordant with international and widely-used classifications, i.e., CPC and ISIC^{19,20}. Breaking down each national sector, a sub-sector means those composed of a fewer number of companies and distributed inner individual prefectures). This limitation of statistical and accounting data has been long lasting for two decades^{15,18,21}. A technological challenge is lacking in measured efficiency data, i.e., subsector water-use per unit of economic value^{15,22,23}, and there remains a dearth of subsector and open water withdrawal datasets. Only Zhou et al. could provide total water withdrawal data before 2013 through simulation based on survey and statistical Ministry of Water Resources data^{24,25}. Yet these data are not fully open or public, and their data-source information is hard to review or trace back. Accounting for water-use data is emerging^{26,27}.

Second, there should be large variation in water efficiencies across regions, and prefecture-level water use patterns are critical but, unfortunately, remain far from known²⁸. Previous studies were based on global^{21,29,30} and Chinese-provincial levels¹⁵, or grid-units at the river basin scale^{31,32}. There is a need to zoom down to administrative and territory-based units, such as the prefecture level for three reasons: 1) a prefecture is typically a basic decision-making and regulatory unit for major and principal policies in China; 2) local governments supply and manage funds for water efficiency management, and local government heads have been appointed as decision-makers for rivers throughout China to conserve water resources. Previous studies noted substantial potential for water saving, yet for a large number of prefectures, the current reporting institution is bottom-up making it difficult to realize potential³³; and 3) scale matters when it comes to water efficiency and scarcity³⁴. Thus there is a need to update with prefecture-detailed information to provide a firm basis for discussion, which would also help coordinate upstream and downstream relationships and solve multi-basin problems due to water use of human activities³⁵.

Third, the regulatory standard is limited to urbanized districts, and excludes rural-areas and suburbs. Rural areas include village enterprises and household consumption, but typically exhibit lower per capita income, and important water consuming activities, such as irrigation in cropland, forestry, animal husbandry and fisheries taking place in suburbs³⁶. Thus such neglect could not reflect overall and synthetic water use or allocation based on the territory. In summary, how to conduct and realize water efficiency ambitions amongst various prefectures or sectors has not been fully answered; control on water use intensities and volumes still lacks targeting to specific users³⁷.

In this study we investigated 161,598 companies with diverse infrastructure, operating throughout China. With an annual industrial output ranging from US\$1466 to US\$8.22 billion, these companies were from 13,377 sector-prefecture combinations. We accounted for datasets on subsector water withdrawal through 13,377 industrial and 1715 agricultural sub-sectors, and water scarcity for all 343 prefectures in China, based on 2015 data. Spatial and economic-sector resolution was improved compared to previous studies^{2,24,30} by splitting general sectors into sub-sectors. This formed the Dataset on Water Use of China at the Sub-sector level (DWUCs). Using this disaggregated and detailed information, we identified the low water-efficiency sub-sectors in prefectures suffering from water scarcity. Then we built scenarios assuming a convergence of below-average water efficiencies to the national sector-average level, through technical improvement amongst industrial and agricultural sub-sectors, respectively (see Supplementary Fig. 1 for illustration).

Taking key prefectures and sectors from China, our results help highlight the best opportunities, enable targeted water-saving strategies, and identify priorities to facilitate water regulation through optimizing efforts for improving efficiency. This study takes both economic scale and water efficiency into consideration to reflect different and marginal water-saving effects. It combines 'targets for water use' and 'targeting to water users' in prefectures and sectors, and should be useful for individual prefectures and sectors to look up detailed water use and efficiency information. Our results should also help promote technology improvement in water-scarce economies including China and other emerging economies³⁸.

Results

Water withdrawal accounts and spatial heterogeneity at the prefecture level

We built up datasets under a general accounting framework for Chinese prefectures using the methodology developed in references^{13,14,22}. From point-source surveys, Fig. 1a, b illustrates maps of industrial water withdrawal intensity (withdrawal per economic output, m³ per million \$) and agricultural irrigation intensity (withdrawal per irrigated area, m³ per m²) at prefecture level. In Fig. 1a, b, there is a clear spatial heterogeneity: the general pattern of industrial water intensity is lower in the southeast and higher in other western regions; whereas the situation for agricultural water intensity is higher in the southwest than the northeast of China. Average industrial water withdrawal intensity was 21,722 m³ per million \$. Industrial water withdrawal intensities were various, with a maximum of up to 2,938,000 m³ per million \$ (for cloth manufacturing, i.e., textiles in Tangshan, Hebei province). Average agricultural irrigation efficiency was 0.668 m³ per m² of irrigated land. Agricultural irrigation intensities were also diverse, ranging to 5.5 m³ per m² (for rice cultivation in Yinchuan, Ningxia province). Here we provide some measure to contextualize these efficiency figures: Average water-withdrawal per industrial value-added at the prefecture level of China is 50 m³ per k-US\$. From a global perspective, this still has a gap compared with the worldwide countries with the most-efficient water-withdrawal at 3.43 m³ per k-US\$ industrial value-added in 2022. Basically, China's water-withdrawal efficiency is comparable to that of the middle-to-high income countries. Meanwhile, water withdrawal per industrial value-added of the US is not the most-advanced, at 34–50 m³ per k-US\$ among different industrial-sectors. If the US data is included, average water withdrawal per k-US\$ (industrial value-added) of the high-income countries would increase from 21.07 m³ to 33.81 m³^{38–40}. This part could be explored in future study.

Figure 1c shows a map of total water withdrawal at the prefecture level. Agriculture water withdrawals were various, from 334 m³ (for wheat cultivation in Nanning, Guangxi) to 4.3 billion m³ (for rice cultivation in Harbin, Heilongjiang). Average agriculture water withdrawal was 212 million m³. Industrial water withdrawals also varied, with a maximum of up to almost 2.0 billion m³ (for production & supply of electricity & hot water in Chongqing; Full names of sector are indicated by & for short, throughout the paper). Average industrial water withdrawal was 16.75 million m³. At the company level, the largest water user was an electricity and hot-water supply company in Ningbo, Zhejiang province (184 million m³).

Overall, 180 prefectures (equating 55% of China's population) were found to be under water scarce condition (measured by criticality-ratio, see Method section for details). Sixty-nine Chinese prefectures (25%) were found to be under extreme water scarcity (27% of China's population). Out of 15 megacities containing more than 10 million inhabitants in 2022, 9 were classified as extremely water scarce, including Shenzhen, Beijing, Shanghai, Chengdu, Tianjin, Qingdao, Suzhou, Shijiazhuang, Zhengzhou, and 14 were water scarce, i. e., plus Guangzhou, Xi'an, Wuhan, Nanjing and Linyi.

The 180 water-scarce prefectures accounted for 70% of industrial output, and 62% of the irrigated area of China. These prefectures supported more than 11% of world exports, responsible for 140 tech-giant companies in the Fortune Global 500³⁹, and 11% global population as of 2022. Yet, these prefectures are diverse in terms of economic activities and irrigation infrastructure. For example, China's industrial outputs vary from US \$123,228 (metal product manufacturing in Honghe, Yunnan) to US\$229 billion (communication equipment, computer & other electronic equipment manufacturing in Shenzhen, Guangdong), averaged at US\$2.46 billion. Irrigated areas are also diverse across prefectures, ranging from 2.29 million m² to 10.72 billion m², with a mean of 1860 million m². These prefectures, and the companies within them, are therefore highly influential within China and globally, and their water efficiency is also hugely important.

Figure 1d shows prefecture economic classifications and their spatial distribution. We classified prefectures into six broad groups: agriculture-based, energy-production, heavy-manufacturing, light-manufacturing,

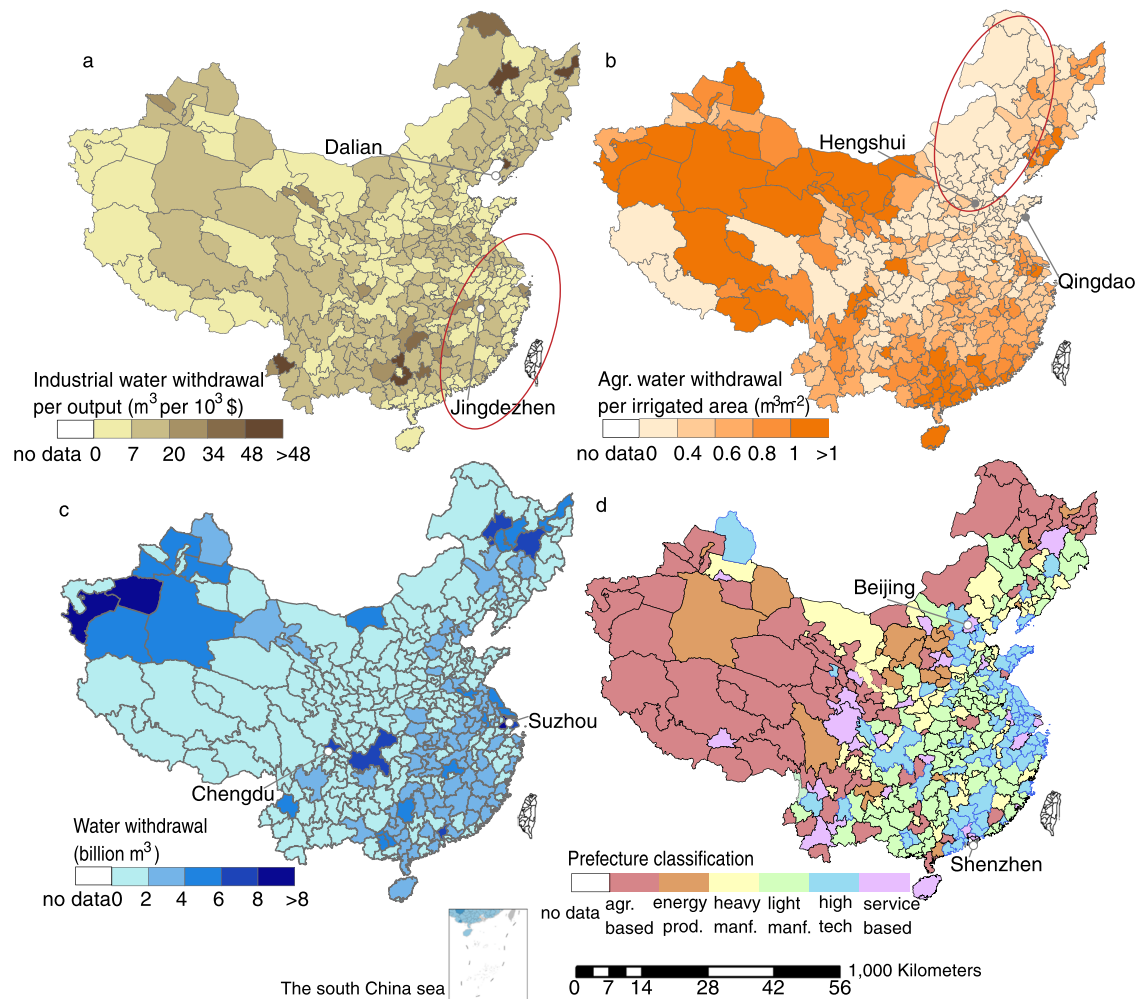


Fig. 1 | Prefectures and their water withdrawal situation. **a** Industrial water withdrawal per output, **b** agricultural water withdrawal per irrigated area, **c** total water withdrawal, and **d** groups of representative sector clustering. The average area

of prefectures was 28 billion m², and average population was more than 4,430,000. The labeled prefectures are discussed in this study.

high-tech and service-based prefectures, using a clustering methodology⁴¹. From an evolutionary perspective, we interpret these six groups as representing different stages of economic development by assuming a development time-lag (see discussions in the Method section). Classifying prefectures also improves the comparability of water efficiency indicators within the same group.

The regional and sectoral heterogeneity in water withdrawal and efficiency at the prefecture level is due to China’s vast territory and high regional-imbalance in water availability (Supplementary Fig. 2a), population, economic structure, and development stages across prefectures (Fig. 1d). In particular, environmental regulation and enforcement may not be as rigorous in less-developed regions^{42–45} (please see Supplementary Discussion 1).

Such regional and sectoral heterogeneity in water withdrawal efficiency highlights that for some sector-prefecture combinations, drastically more water consumption and environmental impact occur than making the same product elsewhere (i.e., industrial competitiveness is hindered). Thus, for high water-intensity sector-prefecture combinations, according to the law of diminishing marginal utility, marginal water-saving costs should be small, and potential for water-efficiency improvements should be large. A lack of consideration of regional and sectoral heterogeneity would result in increased management costs for water savings including land costs, rental income, opportunity costs, and other social costs^{7,46}.

Low efficiencies of super-consumers in water-scarce prefectures

One might expect sub-sectors in water scarce prefectures to adopt water saving technologies, hence their water withdrawal intensities to be lower compared to water sufficient areas. This hypothesis was not verified. We did find a number of water scarce prefectures, such as Qiqihar (north China); Yingkou (east China); Wuhai (west China); and Puyang (central China) with water intensities much greater than prefectures abundant in water resources, Fig. 1a. Although China set water intensity reduction redlines and goals as early as 2011, reducing intensities in water-scarce prefectures should be better targeted towards specific sub-sectors. Prefectures such as Wuhai, Hegang, Puyang, and Qitaihe had water intensities which were still high, but they were not recognized as over-exploiting resources until 2018⁴⁷.

A disproportionately small fraction of sub-sectors contributed to large water withdrawals with low water efficiencies, which should therefore be targeted to save water. Taking 39 industrial sub-sectors as an example, we ranked $39 \times 272 = 10,608$ sector-prefecture combinations by increasing order of water intensity, and then calculated their share of cumulative water withdrawal. We depicted these shares relative to shares of cumulative numbers of sub-sectors, and obtained cumulative distribution of water-withdrawal intensity (Fig. 2m, Lorenz curve). The curve shows that the 10% highest water-intensity sub-sectors disproportionately accounted for 46% of water withdrawals. Such super-consumers were mostly in small and

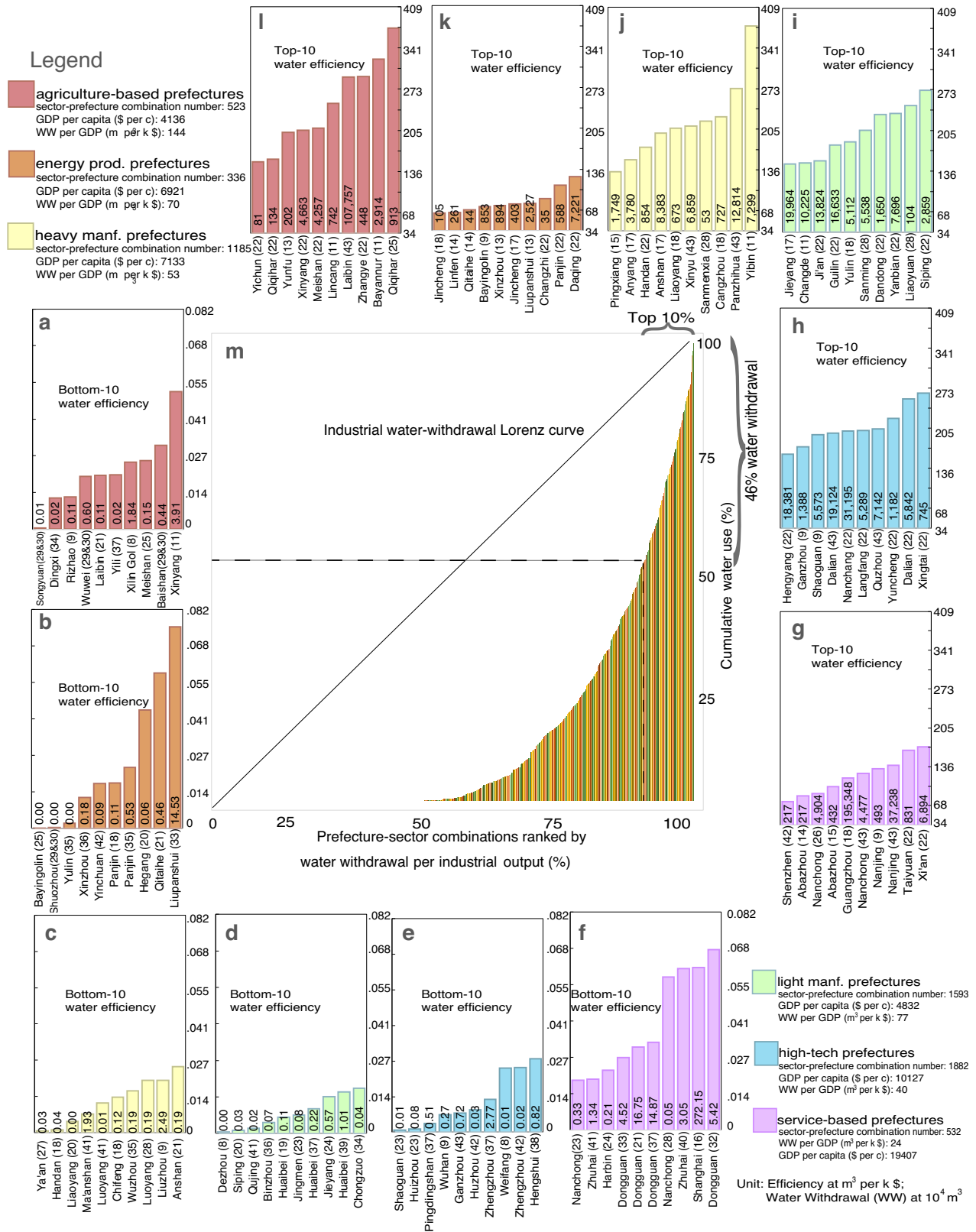
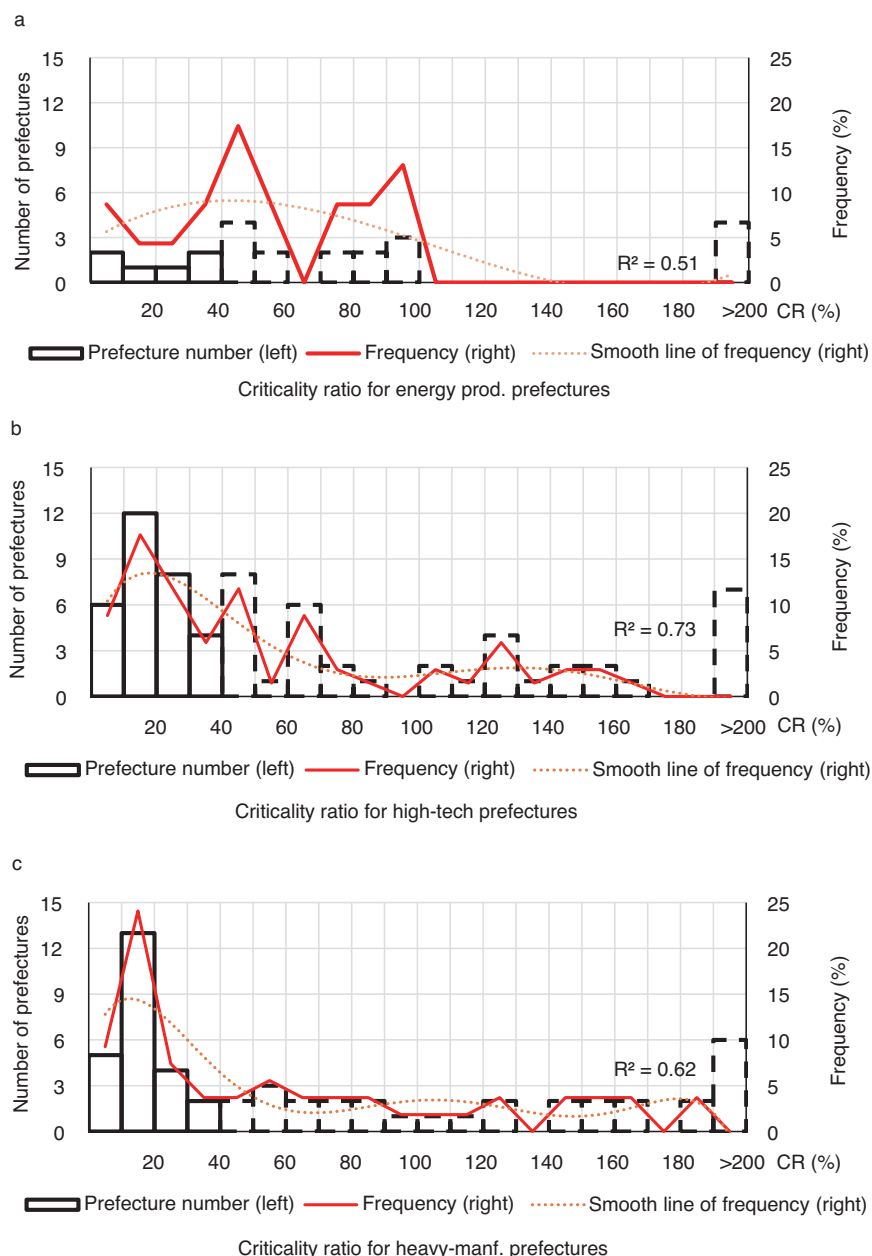


Fig. 2 | Cumulative distribution of water-use intensity showing subsector usage depicted by different efficiencies of 10,608 industrial sub-sectors from six broad economic groups. a–f are the bottom (the lowest intensity) ten sub-sectors for industrial water withdrawal intensity (per economic output) in each of six clusters; **g–l** are the top-ten. They are, accordingly, positioned to the left and right sides

adjacent to x-axis of (m). In (a)–(l), sub-sectors are represented with codes in parentheses; the number on each bar shows water withdrawal (WW) of the individual sub-sector. For average GDP per capita and water withdrawal per GDP, we calculated the sum of the numerator and denominator, respectively, before division.

Fig. 3 | Histograms showing frequency distribution of water stress for representative prefecture-clusters. There are three representative prefecture-clusters, namely energy production (a), high-tech (b) and heavy-manufacturing (c). Criticality ratios above 40%, i.e., water scarce, are indicated by dashed squares. We merged >200% samples due to slightly lower frequencies.



developing prefectures, with representative industries, such as papermaking and product manufacturing in Chenzhou (central China), Lincang (southwest China) and Qiqihar (northeast China); liquor, beverage and tea manufacturing in Jingdezhen (mid-east China), Anqing (mid-south China) and Wuzhou (southwest China); and electricity and hot water supply in Changde (mid-south China). These water-scarce prefectures with sub-sectors of low efficiency and large water-use ought to be targeted, given an understanding of the role of different sectors and prefectures.

In Fig. 2, examples of energy production prefectures include Daqing, Panjin, Changzhi and Liupanshui. Although the top and bottom ten sub-sectors for water withdrawal intensity were the smallest, this group appeared vulnerable since some of them, e.g., Wuhai, Panjin, Hegang, Huozhou and Qitaihe, have exhausted energy and water resources. High-tech prefectures follow, of which examples include Dalian, Nanchang, and Shaoguan. For heavy-manufacturing prefectures, water withdrawal intensities were complex: these are the largest, for example, Panzhihua, Sanmenxia, Anshan and Handan, and water-withdrawal efficiency varies across a broad range. Service-based prefecture water withdrawal intensities are relatively not high. Additionally, some prefectures were also clustered through characteristic

sub-sectors with large water-use, for example, Changchun (heavy manufacturing: special purpose machinery), Suzhou (high-tech manufacturing: communications equipment), and Yangzhou (heavy manufacturing: chemical materials & products).

We compared water scarcity occurrence amongst different prefecture-groups. The most-severely affected were found in the high-tech group (Supplementary Fig. 3); 38 prefectures over the 40% water criticality-ratio (water scarce) and 20 above 100% (extreme water scarce). These were the highest in their corresponding tier, indicating economic growth limitations subject to water resource constraints⁴⁸, as accounted as economic loss of water scarcity⁴⁹⁻⁵¹. Notably, population in high-tech prefectures accounted for 33% of the total, and approximately 200 million people in these 38 prefectures were commonly affected by severe water scarcity. Heavy and light manufacturing prefectures were also ranked, behind high-tech prefectures.

Furthermore, in reference to studies^{52,53}, we found differences in water stress for different prefecture-types, indicating frequency and severity of water scarcity occurrence. For energy production prefectures (Fig. 3), the frequency seemed relatively higher, but not as severe when compared with

the heavy manufacturing group. The frequency curve peaked at 50%, exceeding the 40% definition of water scarcity. In other words, most prefectures appeared to be distributed to the right of the scarcity threshold. Reassuringly, there appear to be relatively few instances of prefectures in the extreme scarcity region (i.e. >100%). In contrast, heavy manufacturing prefectures had lower frequencies of water scarcity occurrence, but once over the 40% threshold, they tended to experience greater severity. The peak in the frequency line appears at approximately 10–15%, i.e., most prefectures tended to be distributed in a narrow band to the left of scarcity threshold. However, there was a greater, more even spread of examples above the extreme scarcity threshold, with a slight frequency of ca. 5% for each distance, so the smooth line tended to decrease gradually. This small subset (ca. 13%) of prefectures in this group mainly influenced our findings for water scarcity in heavy-manufacturing prefectures.

On the other hand, as shown by Fig. 4, improvements in industrial water-reuse rates targeting 94% by 2025, according to ref. 54 (water reuse is water recycled or repeated within a company after first withdrawal), sector-prefecture combinations with low water-reuse rates (i.e., below average) should implement wastewater treatment, common water recirculation, or recycling technologies.

Targeting sectors and prefectures for future efficiency improvements from a global perspective

Referring to studies^{15,55}, we assumed one sector would supply similar products, so that water efficiency indicators within that sector could be compared between prefectures. For individual sectors, we developed two scenarios to consider agricultural and industrial sub-sectors. Scenario 1 was in water-stressed prefectures for agricultural related sub-sectors (scenario 1.1: $5 \times 343 = 1715$ sector-prefecture combinations), and for industrial related sub-sectors (scenario 1.2: $39 \times 272 = 10,608$ sector-prefecture combinations) (Fig. 5). In scenario 2, we assumed China would make water efficiency improvements across all prefectures (scenarios 2.1 and 2.2 in Supplementary Fig. 4). We substituted below-average water efficiencies with averages, assuming that technical progress in water use efficiency would enable low-efficiency sub-sectors to reach average levels. Specifically, technology is a vital factor underpinning different water intensities within one sector. For example, in Suzhou, electricity & hot water supply withdrawals were as much as 5.3 km^3 p.a. (64% of total water use) due to the single-pass cooling technology used in 99% of its thermal plants. Transition to recirculating-cooling water would result in water savings¹⁷. On the other hand, food or general-machinery manufacturing technology in Dongguan and Hanzhong, stood out as high-efficiency examples, and should be seen as benchmarks to peers in their national-sectors.

If the water use intensity of a sub-sector in a prefecture was lower than the national sector-average, we left this water intensity as it was. Similarly, if water use intensity was higher but occurred in a prefecture with no water stress, we did not substitute, either. We only substituted intensities for sub-sectors with above-average water-use intensities in water-stressed prefectures with national sector-averages.

This approach is consistent with the metrics and standards used for instructing water withdrawals throughout China, etc.^{42,49,56}. In fact, a number of prefectures even require sub-sectors to utilize leading-edge technologies and regulatory standards for water savings in production since 2019⁵⁷, i.e., benchmarked against the most efficient technology. Bearing in mind that we found some extremely high-intensity sub-sectors during our point-source surveys, and that there was large heterogeneity in water withdrawal and efficiency across prefectures for one national-sector, we estimated that using the national sector-averages would provide a useful guide.

For water-scarce prefectures, in scenario 1.1 (agricultural related sub-sectors) and scenario 1.2 (industrial related sub-sectors), we estimated that 69.2 km^3 ($\pm 2.56\%$) water savings could be realized. This amount is (1) larger than the average annual runoff of the Yellow River in China (58 km^3), (2) equivalent to four years water demand in Hebei province⁵⁸, (3) approximately six times the total transfer volume of the South-to-North middle-route water transfer project in China, (4) equivalent to the annual water

demand of Russia in 2022 (the second largest worldwide)⁵⁸, or (5) 6.9 billion Olympic swimming pool volumes (nearly one for each individual in the world to-date 2022).

In agricultural related sub-sectors (Fig. 5b, c), a relatively small fraction (10%) of $5 \times 343 = 1715$ sector-prefecture combinations contributed to a large (70%) of the total 50.3 km^3 ($\pm 2.32\%$) agricultural water savings (Fig. 5a). For individual water-scarce prefectures, water savings ranged from $26,553 \text{ m}^3$ in Xinzhou to 6.5 km^3 in Kashi. Figure 5b indicates that rice cultivation, towards the right-hand side of x-axis, could contribute approximately 25% of these water savings, whilst maize cultivation could contribute a 14% reduction. Furthermore, the largest contributions were found to be from a small number of sub-sectors at the prefecture level, for example, rice as shown in Fig. 5c (above the dotted line). Conversely, it was less effective to tap potential savings for national-sectors below the dotted line. Typically, there will be more than a single prefecture-sector combination changed in most national-sectors. Previous studies⁵⁹ recommended consideration of the economic and productive disruption as a way of exploring cost-effective water-saving options. Using the same treatment as the *National Water Saving Action Plan* and the latest research⁴⁹, the change number of sub-sectors in prefectures was used in this study^{60,61}. We assumed a positive correlation: the greater the number of sub-sectors substituted, the greater the economic and productive disruption that implementation of water saving technologies created, and the more human and material resources would have to be input and managed. We estimated the change proportions, in percentage (%).

Interestingly, a minority of sub-sectors could save the most water whilst affecting the fewest prefectures; this would appear a win-win opportunity balancing economic and water-resource imperatives. In fact, most sub-sectors would create greater economic disruption in order to achieve identical levels of water savings. From a subsector water-use efficiency improvement perspective, we therefore recommend water saving initiatives in three key sectors, which potentially contribute 70% of all water savings, namely: rice cultivation (25%), vegetable and fruit cultivation (25%), and fiber and bean etc. cultivation (20%). For example, rice cultivation could contribute 25% ($\sim 12.3 \text{ km}^3$) to total agricultural water savings, yet these sub-sectors account for only 20% of overall substituted sub-sectors at the prefecture level. Requiring all sectors to evenly or in-general improve their water-use efficiency does not therefore represent an optimal policy choice. A list of targeted sectors and prefectures is provided in Supplementary Table 3.

Our findings also apply to industrial sector related water savings (scenario 1.2, Fig. 5d, e). In industrial sub-sectors, reducing high water-use intensities in a small proportion (25.7%) of the 10,608 sector-prefecture combinations would result in a large (63%) fraction of total industrial related water savings. An amount of 18.9 km^3 ($\pm 3.2\%$) water savings could be achieved, equivalent to the annual water demand of Australia, or Hebei province in China. Water savings ranged from $118,700 \text{ m}^3$ in Beijing, to 2.0 km^3 in Guangzhou. We identified four industrial sectors (Fig. 5e) which contribute almost half of the total industrial water-savings, namely: cloth manufacturing, chemical material and product manufacturing, clothing manufacturing, and electricity & hot water supply. Here, cloth manufacturing is textile, including from cotton to intermediate products, such as fiber, yarn, cloth and other materials. Clothing manufacturing is from fiber and yarn etc. to final clothing products, such as apparels, footwears, trims and hats. They pertain to different products and industrial sector-committees.

Note: for brevity, in Fig. 5b, d, we listed a product and a code for each sector; 1–5 are crop cultivation, 7–12 represent mining and processing, 13–42 are manufacturing, and 43–45 are production & supply of electricity, gas & hot water. For full names and descriptions, please refer to Supplementary Table 1. Water-saving uncertainty arose from the treatment of high-intensity sub-sectors during our survey. This is due to the high heterogeneity in water withdrawal and efficiency across prefectures for one national-sector. Gray shading indicates a specific range of intensities (empirical distribution) in each national-sector. Upper and lower

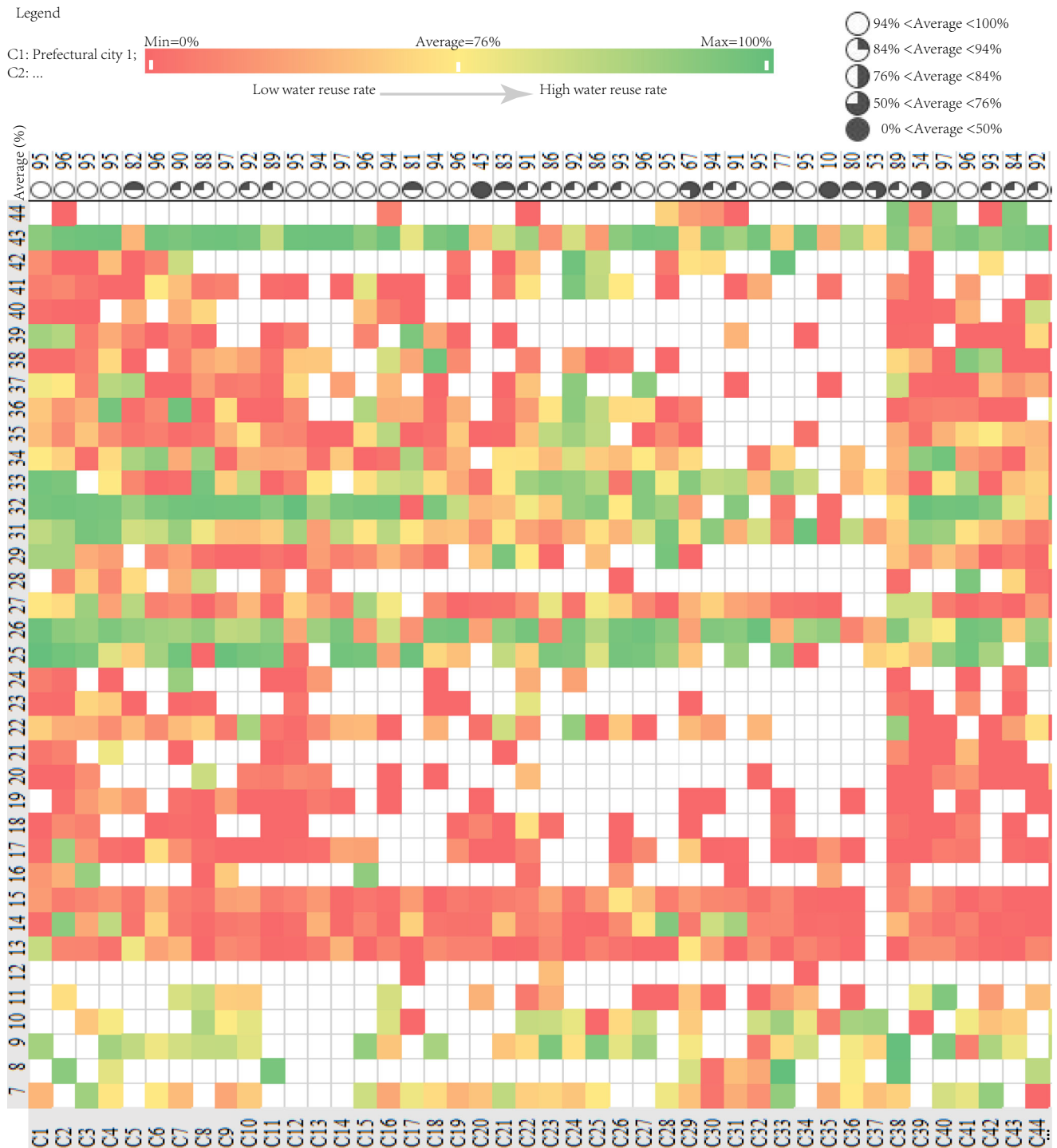


Fig. 4 | Heat-matrix indicating various water reuse rates. The x axis is the code of prefectures and y axis is industrial sectors (7–44). (please see source data for Fig. 4 in Supplementary Table 2).

boundaries were calculated using the three-standard-deviation method. We excluded sectors with quite small contributions.

From a global perspective, we compared eight representative and water-scarce Chinese megacities with countries of first-class water-use efficiencies (Fig. 6). The combined population of these megacities reached to 136 million, averaging 17.05 million in 2022. Overall, the water intensities for the eight water-scarce megacities were not high; in particular Beijing and Tianjin were efficient. Following efficiency improvements, projected intensities for megacities, such as Nanjing and Guangzhou would result in upgraded agriculture, which would transcend the levels of developing

countries (2050) and global (2050) agriculture intensity lines, surpassing the levels of Near East and North Africa countries in 2016 at approximately $0.753 \text{ m}^3 \text{ m}^{-2}$. The projected intensities of Xi’an and Shanghai would be low, to be future new megacities. Agricultural irrigation intensity for Nanjing would be improved to a point lower than the 2050 global agriculture intensity, meanwhile, industrial water withdrawal intensity would cross below the industrial intensity of China under the 2060 carbon neutrality goal, at 3194 m^3 per million US\$. Given that some water-scarce countries, i.e., Australia, Netherlands, Near East and North Africa countries, Italy, Spain and Czech Republic, have deployed cutting-edge water-efficiency

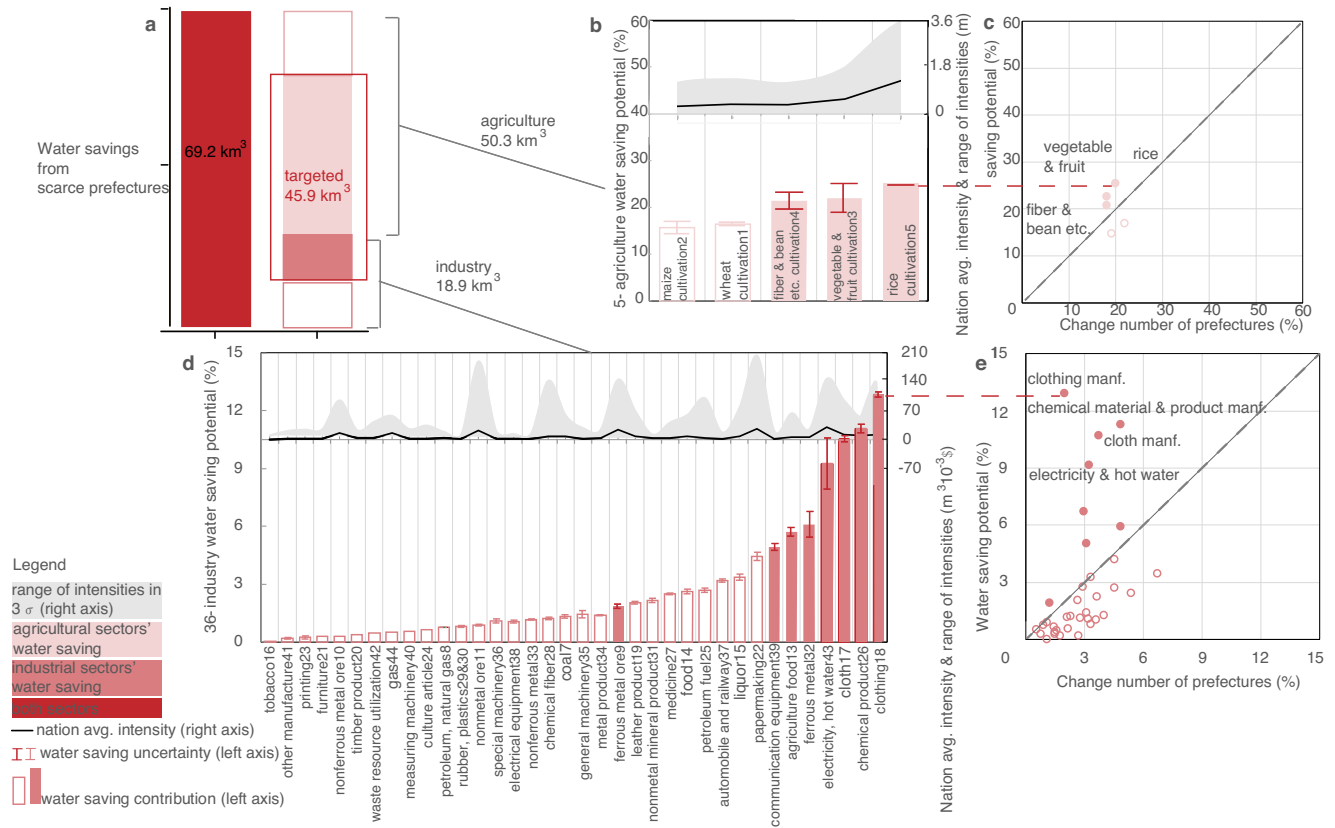


Fig. 5 | Water-saving potential and withdrawal intensity (national average) in the agricultural and industrial sectors. **a** In water-scarce prefectures, **b** and **c** were in agricultural sub-sectors, and **d** and **e** in industrial sub-sectors. A few sectors were large contributors (solid circles, and above the dotted lines of **c** and **e**), whilst it was less effective to tap potential savings from most sectors (hollow circles, and below the dotted lines).

technologies^{18,62}, their worldwide intensities could be benchmarked for Chinese megacities to clarify a pathway. For both developing and developed countries, comparisons with global countries would enable megacities to reduce the gaps to SDG6, carbon peaking and neutrality goals to 2050 and 2060.

At identical water availability levels, 18 Chinese prefectures could reverse their water scarcity status. The population amounts to 40 million people (equating to total population of South Africa, or 2/3 population of UK in 2022), and 5% of total Chinese GDP. Example prefectures include Xining, Zhangye, Hotan and Haidong (northwest China); Jincheng and Yulin (west China); Jilin prefecture (northeast China); and Wuxi and Xiangtan (mid-east China). At national level, the mean scarcity level for water-scarce prefectures would be alleviated to sub-extreme levels, falling by 20 percentage points from 96% to 76%.

Discussion

Given that improving water use efficiency is a slow and difficult process⁶³, and actual achievement of water intensity reductions is likely to be different from our scenario analyses since technologies and evapotranspiration-rates vary between sectors and prefectures⁶⁴, we must consider technological as well as institutional interventions. In fact, China’s water-saving potential in this regard should be substantial, with opportunities for farms and factories to advance efficient and controllable water-use equipment from best practice as cooperation partners in their respective sectors. A great number of fundamental water-saving technologies are already available⁶⁵, to facilitate a late-development advantage of water efficiency regulation from one group of prefectures to another^{24,36,66}. For instance, representative technological improvements in industry include water recirculation, and air- and seawater-cooling in the dyeing of cloth and clothing manufacturing⁶⁷, chemical manufacturing, and power generation¹⁷. Through use of wet towers, water abstraction per kWh could be reduced from 168 liters to 5

liters⁶⁸, indicating substantial room to reduce extensive and wasteful water use in the power sector; in agriculture, technical improvements with the state of the art in China are efficient irrigation techniques applied in rice, vegetable and fruit cultivation in Hengshui and Tongliao prefectures^{69,70}. Cutting-edge mulch planting and water-fertilizer integration have also been developed in Qingdao and Yantai. Beyond China, vertical farming is an available engineering practice⁷¹.

Alternatively, legislating specially for industrial and agricultural water-use rights, transparent water tax, and trade incentives for water-saving sectors and prefectures through water management contracts could be recommended⁷²⁻⁷⁴. Infrastructure investment and indices for leading-edge farms and companies should be regularly updated. Online and real-time monitoring on water withdrawal of key sectors at the prefecture level through roll-out of smart metering is feasible^{77,75}. Beyond China, water pricing with full cost recovery⁷⁶, and water-neutral development⁷⁷ are available to-date.

We summarized seven kinds of mainstream and emerging techniques, i.e., six for irrigation (applicable to cultivation of wheat and maize etc.) and one for power-generation, as listed in Table 1 for detailed information. In this process, on-site visits were used to gather data. We find drip irrigation, for example, requires an initial investment of approximately \$2200 per hectare and an annual maintenance cost of \$880. Large-scale adoption will likely depend on government subsidies, as high upfront costs may deter farmers. In 2014, micro-irrigation area of cultivated wheat of China is 952 k ha. In 2021, proportion of China’s micro-irrigation area in total agricultural irrigation area is 16.89%, according to the International Commission on Irrigation and Drainage (ICID) database⁷⁸. Proportion of micro-irrigation area (11,816 k ha) in water-saving irrigation area (37,796 k ha) is 31%. Towards future, we predict that on one side, large-scale applications of these water-saving techniques are booming globally, especially in developing countries^{79,80}; On the other side, such applications should continue to rely on

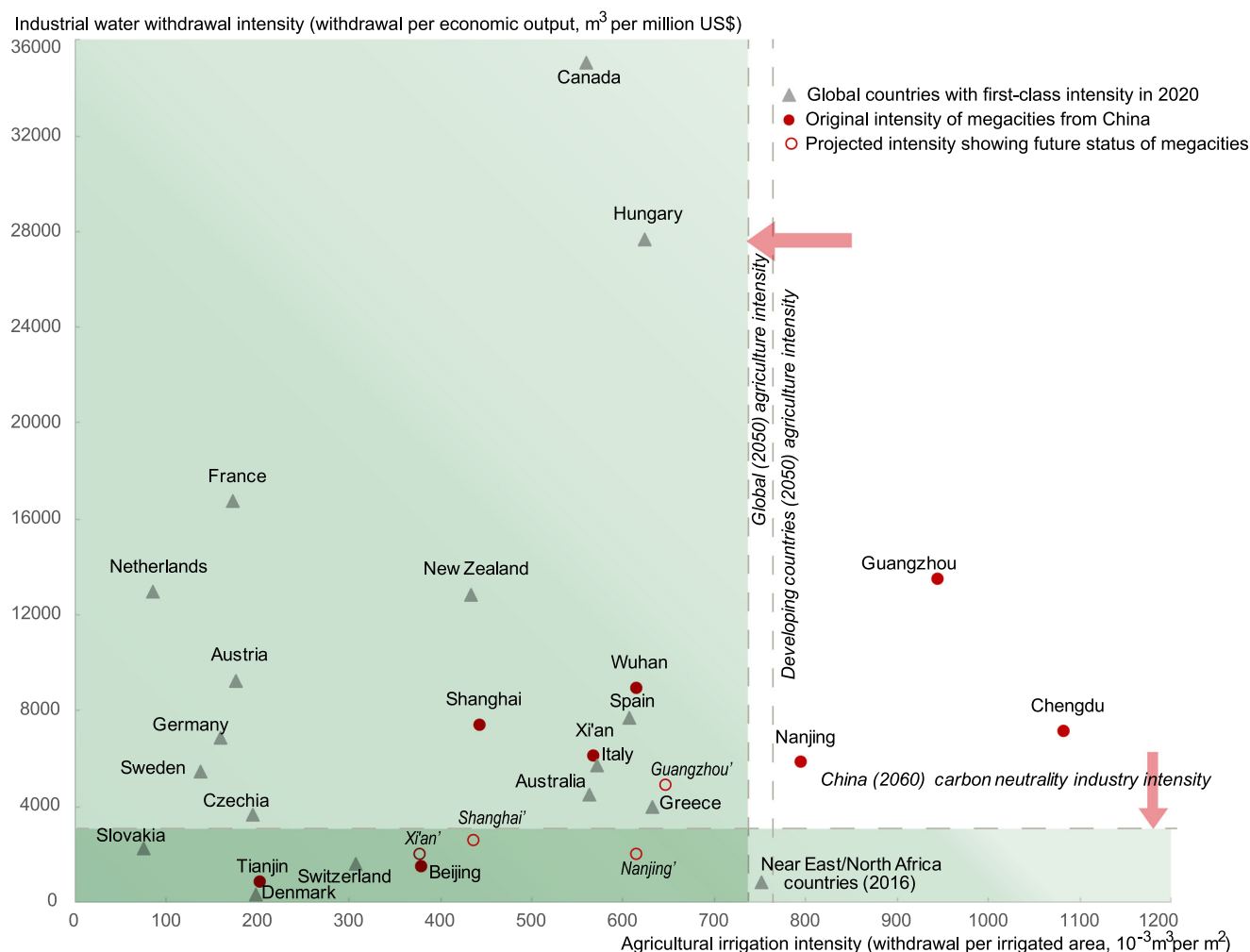


Fig. 6 | Intensity comparison between representative water-scarce megacities and countries. Combining agriculture and industry, the figure shows future change of Chinese megacities. Data for China carbon neutrality industry intensity (2060) were forecasted by the authors based on the study¹⁵, i. e., industrial water withdrawal intensity if China realize its carbon neutrality goal in the year of 2060. Projections for 2050 were obtained from references^{45,63}, and the Organization for Economic Co-operation and Development (OECD) database. Calculations of economic output

were based on the constant prices of 2015. In this figure, every prefecture has two points, which denote before- and after- the improvement, e.g., Shanghai vs. Shanghai', Xi'an vs. Xi'an'. Some quite-advanced prefectures in terms of water-saving have little potential for improvement, and thus present overlapped positions before- and after- the improvement, i.e., these prefectures change quite slightly. (please see source data for Fig. 6 in Supplementary Table 4).

fiscal subsidies and promotions from government, because added inputs usually decrease profits of farmers⁸¹. Currently, farmers alone are unwilling to adopt such water-saving techniques. Future research should explore financial feasibility in greater detail through case studies, examining payback periods and economic impacts (please also see Supplementary Discussion 2).

In summary, this study provides a systematic accounting, and ascertains heterogeneity in prefectures' water-use profile to facilitate a thorough understanding of unbalanced subsector water-saving potential to enable paradigm shifts. We identify the possibility that a small number of sub-sectors, i.e., 25.7% in industrial related sub-sectors and 10% in agricultural related sub-sectors, contributed 63% and 70% of potential water-savings, respectively. A minority of sectors could contribute most to water savings whilst minimizing economic disruption. In contrast, implementing uniform water efficiency measures in the majority of sectors would result in substantial economic change to achieve identical water savings.

Water efficiency improvements should therefore be targeted towards this minority of sectors, i.e., cloth(ing) and chemical manufacturing in industry, and rice, vegetable and fruit cultivation in agriculture. To avoid the one-target-fits-all approach, China should combine 'redline targets for water-use' and 'targeting to water-users' of key prefectures and sectors,

rather than requiring all sectors and prefectures to be involved in water-saving. Focusing on these sector-prefecture combinations would minimize potential economic disruption across the wider economic base.

Based on differences of water scarcity occurrence in different prefecture-types, we also consider different strategies. For heavy manufacturing prefectures, we recommend policy should focus on a small number of water-scarce prefectures at this stage. By comparison, for energy production prefectures, policy makers should focus on a larger number of prefectures. For agriculture-based and light-manufacturing prefectures, given their relatively lower GDP per capita, the balance between economic-development and water-saving needs to be better coordinated in decision-making.

Regarding limitations and future work, the reader should be informed: (1) At this stage, water quality-induced scarcity⁸² has not been included due to a lack of corresponding data; (2) the extent to which water savings could be driven by water stress requires quantitative analysis; (3) in industrial sub-sectors, it will be better to use value-added to substitute output to assess efficiency, when such subsector value-added data are accessible in the future.

And (4) water-saving disruption and cost are worthy of further exploration. We acknowledge that at the corporate level, water efficiency improvements do not necessarily lead to increased operational costs. In this

Table 1 | A scheme of seven mainstream and emerging water-saving techniques

Sub-sector	Type	Measure or technique	Definition	Saving potential (%)	Current status or area	Feasibility		Prospect (↑↓)
						Cost, expenses for applications (\$)	Optimal water use amount (m ³)	
Agricultural irrigation	Micro-irrigation	Drip irrigation ^{79,119–121} ; Subsurface drip (SSD); surface drip (SD)	40% in soil surface wetted ^{9,66}	50–80 ^a	Small area and expansion	Fixed investment: 2200 per ha, plus 880 per ha per year for mulch etc. consumable ^b	1800 per ha (winter wheat) ¹²² , 5907 (corn)	Continuous expansion, to be leading, with fertilizer & plastic mulch techniques ^{79,80,119}
		Sprinkler irrigation	60% in soil surface wetted ^{9,66}	30–60	485 k ha for wheat ^c	Cost higher than benefit; 75% irrigation time shortened.	N.A.	To decline in cultivated area
	Irrigation through pipelines	Bubble irrigation	N.A.	30	N.A.	N.A.	N.A.	N.A.
		Low pressure pipelines	N.A.	15–30	11,517 k ha	N.A.	N.A.	N.A.
Industrial power generation	Canal seepage control	Canal leakage control	N.A.	15–30	N.A.	N.A.	N.A.	N.A.
	Furrow & canal	Canal & furrow	80% ^{79,80} , usually based on a constant interval ⁸³ , without moisture monitor	15	Dominating in China ^{79,80}	N.A.	6822 per ha (corn)	To sharply decrease in cultivated area
	Water recirculation cooling	Wet towers	Transition from single-pass to recirculating-cooling	97%, from 168 liters to 5 of water abstraction per kwh ⁶⁸	Less than 10% thermal plants ^d	Total generation costs at 0.05 per kwh ^{86,123}	159 million for electricity & hot water supply	Substantial room to reduce ¹⁷

Full names of sector are indicated by & for short, throughout the paper.

Please see Supplementary Discussion 2 on technology cost and water policy.

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

^aThere is no substantial gap in water-saving potential between SSD and SD. Data are from Tianjin in 2023⁵¹.

^bFor Zhangbei county in Hebei province, north China.

^cData is in 2014.

^dFor Suzhou, in Jiangsu province, east China.

regard, water saving would also bring economic benefits. Future research will explore financial feasibility in greater detail through case studies, examining payback periods and economic impacts; (5) we only considered direct water savings. Consumption-based water accounting considers water savings throughout the entire supply chain, which would be practical in future work; and (6) this study did not consider integration across industrial and agricultural related sub-sectors, yet an option to save water is to treat wastewater and reuse it in agriculture, e.g., 80% of industrial water is reused in Israel in the international context⁸³.

Methods

Of 343 prefectures, 272 prefectures were accounted for subsector industrial blue water withdrawal datasets (limited by data availability of subsector industrial output), and all 343 prefectures were further accounted for sub-sector agricultural blue water withdrawal, total blue water withdrawal, and quantitative water scarcity status. The population of the 272 prefectures represented 88% of the total population of China.

Prefecture-level water withdrawal accounting framework and data sources of DWUCs

Water accounting in China has fallen behind compared to other developed countries¹⁶, such as Australia, the U.S. and France^{84–86}. 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.⁸⁷. Here we took the U.S. 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, the CEO Water Mandate is aimed at the ability of companies to measure and communicate water in a consistent manner^{20,88}. It proposes and promotes the most cutting-edge water topics, such as urban and local water-use information disclosure from large companies, water valuation, and return on investment, etc., to improve water resilience. Nevertheless, similar topics are not discussed or progressed in China.

Similarly, water accounting in Australia has been a well-known program presenting water-use information since 2000. For example, Australia has a water accounting framework in the mining and metals industry⁸⁹. Prior to this approach, monitoring, measuring, and reporting on water use were often inconsistent between sites within companies or across sectors. To address this inconsistency, a framework was developed by the University of Queensland Sustainable Minerals Institute. Following more than six years of revision, exploration and data accumulation, the 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 benchmark performance on water withdrawal efficiency. In contrast, water withdrawal statistics in China were patchy, and water data across all sub-sectors at the prefecture level appeared to be relatively insufficient¹⁶. Not all prefectures in China are able to account for water as routine management activities, as in Australia, America and France^{84–86} etc. Approximately two fifths of 343 prefectures do not collect or develop water data statistics. For data of the other three fifths of prefectures, there are only total numbers of six types provided, with differences in terms of statistical caliber etc. In summary, there remains a dearth of subsector, open and systematic water-withdrawal datasets for China.

We therefore applied our general accounting framework^{13,14,22}, and built up prefecture-level and territory-based water withdrawal data for each sub-sector (the Dataset on Water Use of China at the Sub-sector level, DWUCs), in accordance with the Intergovernmental Panel on Climate Change (IPCC) administrative boundary (scope 1)^{90,91}. A prefecture was defined as a sub-provincial administrative unit, including leagues, regions and autonomous prefectures. The boundary of a prefecture spanned both rural and urban geographies, distinguished from built-up districts¹⁸. 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 for all types of water withdrawal within a prefecture boundary: farming, forestry, animal

husbandry, fisheries, industry, construction, service, household, and ecosystem and environment preservation.

In this study, we assume water use equating to water withdrawal. Water withdrawal is a newly withdrawn water amount allocated to end users¹². This variable may depict pressure on available water resources from local economic activities more accurately since it excludes reused water^{13,14,22}. We did not consider loss in transportation after withdrawn.

Core and primary data of the Dataset on Water Use of China at the Sub-sector level (DWUCs) are from national pollution point-source census of the Ministry of Ecology and Environment. In the census and survey, we investigated 161,598 companies (approximately 42% of all above designated-size companies of China; above designated-size company referred to those with annual business revenue over 2.93 million US\$⁹²; exchange rate at US\$1 = ¥6.8174). Apart from carbon emissions, water withdrawal information collection was conducted, and industrial economic-output data were coupled with water-withdrawal data of companies. Then these data were subsequently aggregated according to sub-sectors to calculate the intensities, i.e., water withdrawal intensities for individual sub-sectors in each prefecture across 13,377 industrial sub-sectors for all 343 prefectures.

Our methodology applies a water balance principle between prefectures and provinces, i.e., water balance equations between provincial water use and its administered prefectures' water-use amounts²⁴. Adopted from the IPCC principles and elements^{90,91}, construction of our datasets was based on selection of 16 driving forces, according to each broad type. For example, disaggregated industrial output and water withdrawal per output of each sub-sector (*Intensity*). We connected a size indicator with corresponding water-withdrawal efficiency. Mechanisms of accountings for the other sectors are similar.

First of all, we need to do data-mining aiming at the 16 indicators, mainly from provincial and prefecture-level water resources bulletins issued by the *Ministry of Water Resources* and local *Hydrology and Water Resources Investigation Bureaus*, national pollution source census and regular reporting systems of the Ministry of Ecology and Environment, and provincial and prefecture-level statistical yearbooks (Supplementary Fig. 5). Then, we move into detailed estimations. We used a complete set of equations to describe all variables. Specifically, ① industrial water use (*WaterIndus*) accounting is as follows: we followed three procedures (A–C), and realized the prefecture level (B) partition, and then the sub-sector level (C).

For (A), we compiled industrial water withdrawal for prefectures in a province from provincial water resources bulletins. There were two cases to consider based on data availability (please also see Supplementary Fig. 5 for intuitive illustrations):

Case 1) If water resources bulletin for a province provided industrial water withdrawal for every administrative prefecture, these data were compiled for later use in subsector partition. We allocated water withdrawal into each disaggregated sub-sector (in Supplementary Table 1) for each prefecture.

Case 2) If the water resources bulletin did not provide water withdrawal for industrial type for all administrative prefectures, we collected industrial water-withdrawal for each prefecture in their corresponding water resources bulletins. For those prefectures that did not have these data in their respective bulletins, we calculated the difference between provincial water withdrawal and the sum of water withdrawal for all prefectures that did have statistics in their prefecture-level water resources bulletins, based on a water mass balance. In this way, we obtained a sum for all prefectures for which water withdrawal of industrial type was not included in their water resources bulletins.

For (B), we allocated the sum of industrial type for those prefectures without statistics, based on two multipliers as driving forces of water withdrawal. We used total industrial value-added (*Valueadded*, size indicator) multiplying water withdrawal per value-added (*Intensity*) in the partition. According to data availability, for prefectures having data for both water withdrawal per value-added and total industrial value-added, we

immediately obtained:

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

$$WaterIndus_i = W_i \times SUM_{n_cities} \quad (2)$$

where i is a prefecture without statistics in the province and n represents the total number of prefectures without statistics in the same provinces. Industrial water withdrawal per value-added was sourced from water resources bulletins at the province and prefecture levels⁹³. Total industrial value-added was from province or prefecture statistical yearbooks. This case was considered to be a further step, going beyond previous studies, such as Guan et al.⁹⁴, which assumed industrial water withdrawal per value-added was identical amongst regions. In the case of missing water intensity, we instead used total industrial value-added to calculate proportions to disaggregate water withdrawal.

For (C), we used disaggregated industrial output and water withdrawal per output of each sub-sector ($Intensity_{i,k}$) to partition total industrial water withdrawal of each prefecture ($WaterIndus$). That is,

$$W_{i,k} = Intensity_{i,k} \times Output_{i,k} / \sum_{k=7}^{45} (Intensity_{i,k} \times Output_{i,k}) \quad (3)$$

$$WU_{i,k} = W_{i,k} \times WaterIndus_i, k \in [7, 45] \quad (4)$$

where k represents a sub-sector of prefecture i , and $WU_{i,k}$ is the subsector industrial water withdrawal of prefecture i . $W_{i,k}$ is the proportion of subsector and industrial water withdrawal in total industry water withdrawal. $Intensity_{i,k}$ is the disaggregated water withdrawal intensity. $Output_{i,k}$ is subsector and industrial output of each sub-sector. $WaterIndus_i$ is total industrial water withdrawal of prefecture i . Subsector industrial outputs were sourced from the statistical yearbook for each prefecture. These data were then proofed and corrected by the authors, according to the China City Statistical Yearbook. We regarded the China City Statistical Yearbook as consistent and true magnitudes. Industrial total water withdrawal and water-withdrawal per value-added were collated from water resources bulletins at province and prefecture levels.

In the prefecture module, methods of accountings for the other sectors' water use are similar as Industry. Concretely, estimation on agriculture water-use amount equates,

$$WU_{i,k} = Irriareas_{i,k} \times Intensity_{i,k}, k \in [1, 5] \quad (5)$$

We used the irrigation water withdrawal per mu of farmland, and the irrigation area to determine agricultural water use. $WU_{i,k}$ is irrigation water withdrawal of prefecture i for agriculture, $Irriareas_{i,k}$ is irrigation area of prefecture i for agriculture (represented by farming), and $Intensity_{i,k}$ is irrigation water withdrawal per mu of prefecture i (mu is Chinese acre, $1 mu \approx 667 m^2$). 1–5 denote the first five of 63 economic activities. Irrigation area was from provincial statistical yearbooks. Irrigation water withdrawal per mu for farmland was sourced from water resources bulletins at the province and prefecture levels⁹³. As there is little uncertainty, this case is considered an advancement of previous studies, such as Vardon et al.⁸⁴, which used only the irrigation area by assuming that the irrigation water withdrawal efficiency was equal among regions.

③We utilized the floor space of housing ($Flospac$), and the water withdrawal per unit ($Intensity$) to estimate water withdrawal for construction. Estimation on construction water-use amount equates,

$$WU_{i,46} = Flospac_{i,46} \times Intensity_{i,46} \quad (6)$$

where $WU_{i,46}$ is original water withdrawal of prefecture i for construction, $Flospac_{i,46}$ is floor space area of housing of prefecture i for construction (represented by completed floor space), and $Intensity_{i,46}$ is water withdrawal per floor-space area of housing of prefecture i . Water withdrawal per floor space of housing completed was from the Bulletin of 1st Water Resources Census (i. e., 2nd Water Resources Census of Shanghai by the Shanghai Bureau of Statistics and Water Authority). Floor space of housing was from provincial statistical yearbooks.

④For water withdrawal for accommodation & catering sector, which is usually the largest water user in the service, we assumed a positive correlation between water use and the number of employees, and then used employment and water withdrawal per employee ($Intensity$). Estimation on service water-use amount equates,

$$WU_{i,49} = Employment_{i,49} \times Intensity_{i,49} \quad (7)$$

$$WU_{i,k} = Employment_{i,k} \times Intensity_{i,k}, k \in [47, 48] \cup [50, 60] \quad (8)$$

$WU_{i,49}$ is original water withdrawal of prefecture i for accommodation & catering sub-sector, $Employment_{i,49}$ is number of employees of prefecture i for accommodation & catering sub-sector (as key water user), and $Intensity_{i,49}$ is water withdrawal per employee of prefecture i . Similarly, $WU_{i,k}$ is original water withdrawal of prefecture i for the other services other than accommodation & catering sub-sector (as ordinary water users), $Employment_{i,k}$ is number of employees of prefecture i for the other services other than accommodation & catering sub-sector, and $Intensity_{i,k}$ is water withdrawal per employee of prefecture i . Water withdrawal per capita in representative accommodation & catering, water withdrawal per capita in other services, were from the Bulletin of 1st Water Resources Census (i. e., 2nd Water Resources Census of Shanghai by the Shanghai Bureau of Statistics and Water Authority). The number of employees in accommodation & catering and other services were from China City Statistical Yearbook.

⑤We 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. Estimation on household water-use amount equates,

$$WU_{i,k} = Popul_{i,k} \times Intensity_{i,k} \quad (9)$$

$$W_{i,k} = WU_{i,k} / \sum_{k=61}^{62} WU_{i,k}, k \in [61, 62] \quad (10)$$

where $WU_{i,k}$ is original water withdrawal of prefecture i for household, $Popul_{i,k}$ is rural (or urban) population of prefecture i (represented by number of permanent residents), and $Intensity_{i,k}$ is household water withdrawal per resident in rural (or urban) areas of prefecture i . $W_{i,k}$ is the proportion of rural (or urban) household water withdrawal in total household water withdrawal. 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 prefecture statistical yearbooks.

After completing prefecture module estimations, subsector module equations contain

⑥Estimation on construction and service water-use amounts equate,

$$WU_{i,k} = WU_{i,k} / \sum_{k=46}^{60} WU_{i,k} \times (WU_{i,UrbanPublic}), k \in [46, 60] \quad (11)$$

We used the proportions of water withdrawals (original magnitude indicated by $WU_{i,k}$) in construction, accommodation & catering and other services, to separate urban and public water withdrawal. This procedure is

more plausible than that used in Guan et al.⁹⁴, which assumed that the water efficiencies of construction and all services were the same. $WU_{i,k}$ is disaggregated and subsector water withdrawal for construction and services of prefecture i . $WU'_{i,k}$ is the original and subsector water withdrawal for construction and services of prefecture i . $WU_{i,UrbanPublic}$ is total urban and public water withdrawal of prefecture i . Please note that the public water withdrawal in urban areas is defined as the sum of the water withdrawal for construction and all the services. This definition of water withdrawal is a statistical feature that is different from other energy, resource or economic statistics.

Ⓞ Estimation on household water-use amount equates,

$$WU_{i,k} = W_{i,k} \times WU_{i,Household}, k \in [61, 62] \quad (12)$$

$W_{i,k}$ 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 sub-sectors, on an occasion that we could only get a total number of household water-withdrawal. $WU_{i,k}$ is disaggregated and subsector water-withdrawal for rural or urban household of prefecture i . $WU_{i,Household}$ is total household water-withdrawal of prefecture i .

Ⓞ We used the area of green land, irrigation volume per green-land area (*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 preservation water-withdrawal. Estimation on water-use amount of ecosystem and environment equates,

$$WU_{i,63} = Greenland_{i,63} \times Intensity_{i,63} + Sanitarea_{i,63} \times Intensity'_{i,63} \quad (13)$$

where $WU_{i,63}$ is water withdrawal of prefecture i for ecosystem and environment, $Greenland_{i,63}$ is area of green land of prefecture i (represented by urban green land areas at this stage), and $Intensity_{i,63}$ is irrigation volume per green-land area in urban areas of prefecture i . $Sanitarea_{i,63}$ is environmental sanitation areas of prefecture i , and $Intensity'_{i,63}$ is water withdrawal per unit of prefecture i . Irrigation water withdrawal per green-land, and water withdrawal per environment and sanitation area, were from the Bulletin of 1st Water Resources Census (i. e., 2nd Water Resources Census of Shanghai by the Shanghai Bureau of Statistics and Water Authority). Environmental sanitation area was taken from statistical yearbooks for each prefecture. Green land area was from China City Statistical Yearbook. Detailed meanings of abbreviations are also shown in Supplementary Fig. 6 and Supplementary Table 5.

Besides, in the subsector module, for farming subdivisions, we calculated proportions of irrigation for cultivation of five main crops in 343 prefectures from Zhou et al.²⁴. Water withdrawal per irrigated area by crop was calculated based on the irrigated area data from Zhou et al.

Overall, approximately two fifths of 343 prefectures do not collect or develop water data statistics, i.e., categorized into the Case 2. For data of the other three fifths of prefectures, there are only total numbers of six types provided, i. e., categorized into the Case 1. Concretely, prefectures from Jiangsu, Zhejiang, Guangdong, Anhui, Hainan, Heilongjiang, Tibet, and Jilin were categorized as Case 2. The remaining prefectures were in Case 1.

We performed sensitivity analyses. Overall speaking, for Case 2 on estimations for prefectures without water withdrawal statistics, water withdrawal efficiency was an essential part of the inventories' uncertainties. We 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, compared to estimations with regional intensities. There was little uncertainty for Case 1. For detailed methodological validation, please also refer to Supplementary Methods 1 (Sensitivity analyses), and detailed discussions in references^{13,14,22}, and Turner et al.⁹⁵. Please also see the 'Supplementary Data 1' file for data quality and improvements.

Application of criticality ratio as an indicator for water scarcity

In terms of measuring water scarcity, the Falkenmark indicator is a well-known measurement of water shortage, with per capita renewable water resources⁹⁶, nevertheless, it does not reflect the environmental flow requirement^{21,97}. The criticality ratio (%) is a classical indicator of blue water and quantitative scarcity^{98,99}, connecting anthropogenic water withdrawal with natural water quantity, and taking into consideration both environmental flow^{100,101} and natural biodiversity¹⁰².

The criticality ratio was determined by dividing total freshwater withdrawal (Fig. 1c) by water availability (Supplementary Fig. 2a) for each prefecture annually¹⁰³⁻¹⁰⁵, i.e.,

$$Criticality_ratio_i = \frac{\sum_{k=1}^{63} (Water_use_{i,k})}{Water_availability_i} \quad (14)$$

where i represents a prefecture; k stands for a sub-sector of prefecture i ; $\sum_{k=1}^{63} (Water_use_{i,k})$ is the total amount from farming, forestry, animal husbandry, fisheries, industry, construction, service, household, and ecosystem and environmental preservation (for more descriptions, please refer to Supplementary Table 1). $Water_availability_i$ is collated from water resources bulletins at the province and prefecture levels, referred to previous studies^{34,93,106,107}. Notably, in 2015 China's precipitation (and water availability) is 2.8% (0.9%) higher than, but close to, its average through multiple years (1957–2022, with statistics)¹², thus the 2015 data are representative.

Empirically, above-40% is regarded as high water-scarcity status^{30,108,109}, and over 100% as extreme water-scarcity, signifying that annual water withdrawal exceeds renewable water resources¹¹⁰. This indicates unsustainable development: local unrenewable water resources would decline, the ecological water-cycle would destruct¹¹¹; urgent water transfer would be required. The higher the ratio is, the more stress is placed on available water resources from withdrawal, and the greater the occurrence of water scarcity^{33,108}. For example, in Supplementary Fig. 2b, the median water criticality-ratio was 47%, varying between 0.38% in Ganzi (southwest China) to over 200% in Jiayuguan (arid northwest China). This median was seven percentage points higher than the scarcity threshold of 40%.

Clusters on prefecture classification

Cluster analysis usually refers to the magnitude of a series of pre-provision indicators (or variables) for specific datasets¹¹²; differences within a cluster would be small, whilst relatively large between groups, i.e., clusters represent variables with similar attributes^{113,114}. Beyond administrative or provincial territories, prefecture-level studies^{115,116} concerning resource use across sectors have utilized a k-mean cluster methodology to classify Chinese prefectures into different groups⁴¹. Similarly, we employed proportions of industrial output, and updated with an agriculture-based grouping. Agriculture-based prefectures occupied greater proportions of farming, forestry, animal husbandry, & fisheries in their GDPs than the other prefectures.

From an evolutionary perspective, we thought six groups could be used to represent different stages of economic development by assuming a development time-lag. For example, representatives of service-based prefectures were so-called first-tier megacities, including Beijing, Shanghai, Guangzhou, Shenzhen, as well as provincial capitals, such as Wuhan and Nanjing. These megacities were typified as wealthy and industrialized economies, as demonstrated by average per capita GDP of US\$19,408. This cluster ranked first in all six groups and enjoyed a GDP of more than twice that of energy-production prefectures. Service-based prefectures were assumed to take a leading position for industrialization processes in all Chinese prefectures.

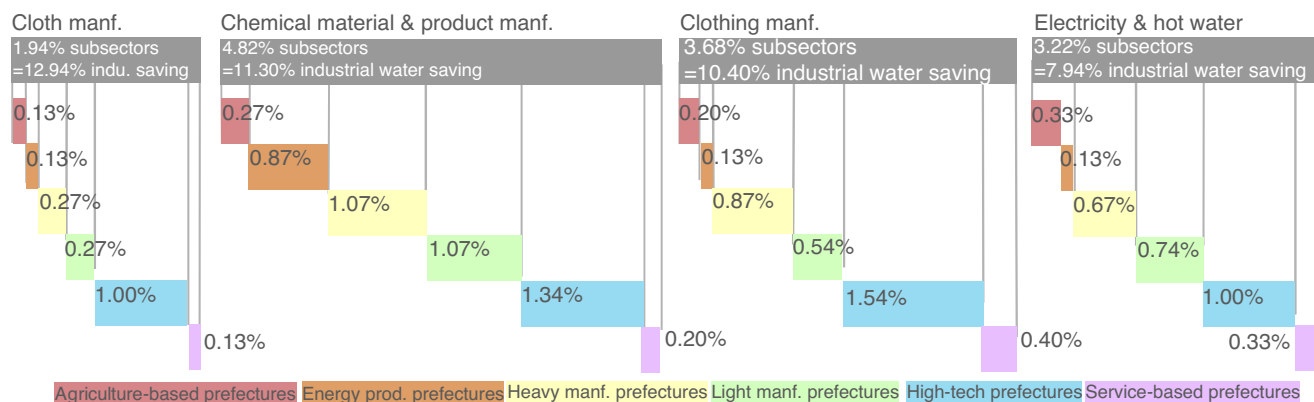


Fig. 7 | Top four industrial sectors of water-saving potential and their structure within different prefecture-groups.

Regarding verification, firstly for a sensitivity analysis on clustering, we grouped prefectures based on economic share of GDP for primary, secondary and tertiary industries, then classified prefectures into three groups. We found only minor differences between ratios of prefectures at individual water-scarcity levels from the groups using proportions of industrial output. Specifically, for agriculture-based prefectures, the >40% and >100% criticality-ratios accounted for 46% and 17%, respectively; for industry-based prefectures they were 54% and 25%; whilst for service-based prefectures they were 67% and 35%. Although clusters were based on different indexes, there were only minor differences in water-scarcity status. We also verified water withdrawal per GDP of agriculture-based prefectures of 150 m³ per 10³ US\$ (exchange rate at US\$1 = ¥6.8174), which was close to the magnitude of representative agricultural provinces, such as Heilongjiang at 143 m³ per 10³ US\$¹⁷. They suggest our prefecture cluster results are robust.

Furthermore, water savings from cluster details also validate our discussion on substitution. In water-scarce prefectures, industrial water savings reached 7.90 km³ for high-tech prefectures, 4.17 km³ for heavy-manufacturing prefectures, 3.40 km³ for service-based prefectures, 2.71 km³ for light-manufacturing prefectures, 0.7 km³ for energy-production prefectures, and 0.62 km³ for agriculture-based prefectures. With water savings in industrial sub-sectors only, heavy-manufacturing prefectures could be alleviated by 11% on average, taking them from extreme to moderate levels. We also decomposed the structure of the top industrial sector-fraction into different prefectures and groups. Figure 7 shows proportions of affected sub-sectors from individual prefecture-groups, respectively. The most severe water-scarce prefecture-groups were effectively pinned down, such as high-tech, heavy- and light- manufacturing prefectures. These prefecture-groups held the top three places for potential efficiency improvements. For example, proportions of affected prefectures (sub-sectors) in heavy-manufacturing and high-tech prefectures were all highest; 78% (37%) and 56% (26%), respectively. This result is also verified by a previous study¹⁸. Thus, we are able to reliably and robustly validate our discussion on substitution.

Finally, in addition to the water efficiency substitution in water scarce-prefectures, we assumed China would also make water efficiency improvements across all prefectures, so that our findings enable a robustness comparison. In Supplementary Fig. 4, we estimate in industrial related sub-sectors, 41.91 km³ (±4.45%) water withdrawal could be saved. We compared this amount with the total industrial water-consumption amount (21.52 km³) in 2022 and found this water saving was higher (almost double). For the Jing-Jin-Ji agglomeration, 0.96 km³ (±9.8%) water could be saved. In the agricultural sub-sectors, 84.0 km³ (±2.07%) water-saving could be achieved.

Data availability

All our data (.xlsx) are transparent and available for free sharing and public use, accessed at <https://doi.org/10.6084/m9.figshare.c.6394068.v1>. We used Microsoft Excel (Office 365) and ArcMap (10.3.1 version).

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Zongyong Zhang, Yuli Shan, Philippe Ciais, Hong Yang, Bofeng Cai, Junguo Liu, Dabo Guan, Heran Zheng, and Yu Hao conceived and designed the experiments; Zongyong Zhang, Xu Zhao, Bofeng Cai, Jingwen Huo, Wanqing Wang, Wang Kai, and Guanlin Li performed the experiments; Zongyong Zhang, Xu Zhao, Zhao Zeng, Dandan Zhao, and Xian Li analyzed the data; Yu Hao, Yuli Shan, Bofeng Cai, Dandan Zhao, Junguo Liu, Xu Zhao, Geng Niu and Dabo Guan contributed materials and analysis tools; Martin Tillotson, Xu Zhao and Zongyong Zhang wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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