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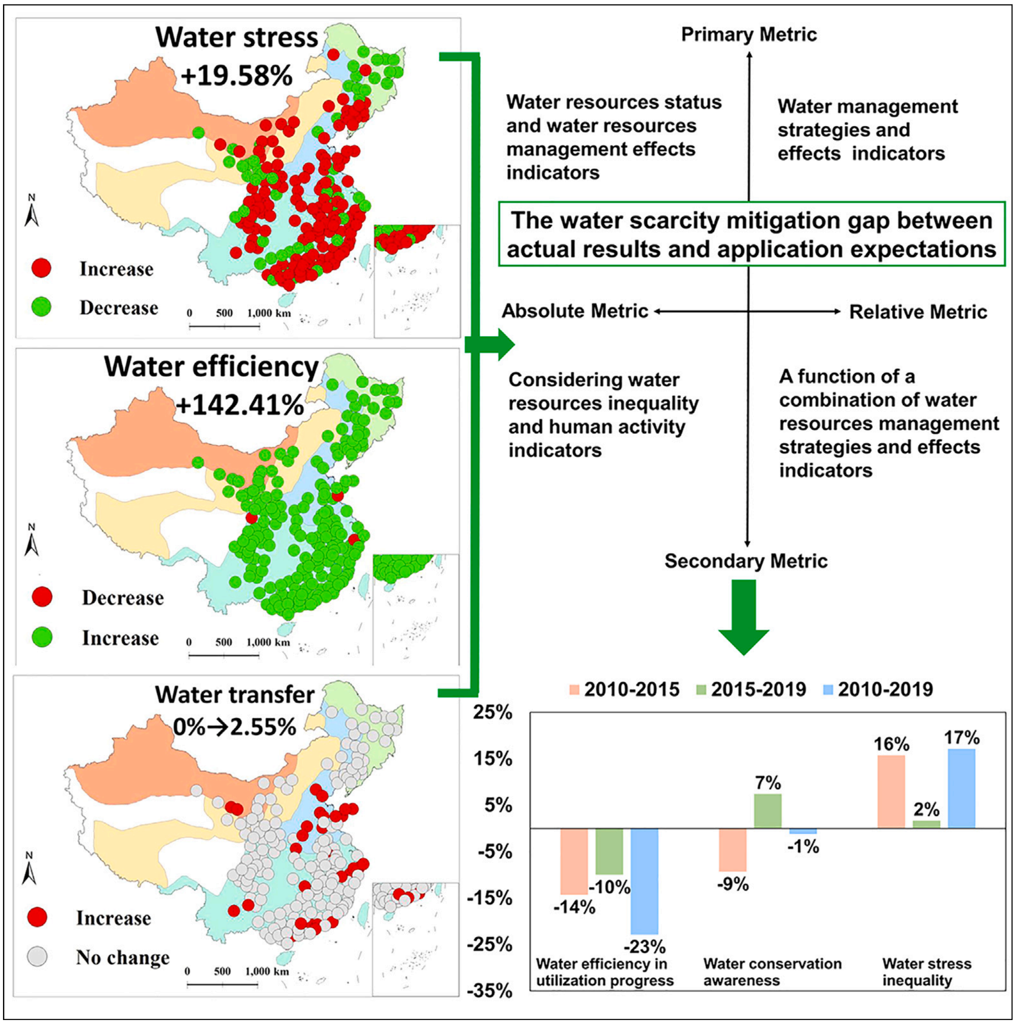

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Highlights

Quantitatively evaluated the trends and effects of water resources management

There are unintended effects caused by human behavior in water resources management

Transferred water resources were not utilized sparingly in the receiving cities

Improving efficiency can mitigate water stress but offset by population growth

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Improving water efficiency is more effective in mitigating water stress than water transfer in Chinese cities

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SUMMARY

The interactions between human and natural systems and their effects have unforeseen results, particularly in the management of water resources. Using water stress mitigation as an example, a water resources management effect index (WRMEI) was created to quantitatively evaluate the trends of water management effects. This revealed that the WRMEI was decreasing due to the impact of the water resources management process. The findings demonstrate that water resources management has unintended effects: there was a gap between the expectation of water stress to be mitigated and the actual results of water stress increasing. That is caused by human activities in water utilization: (1) increasing available water resources from water transfer was not utilized sparingly in the receiving cities—increased water transfers from external sources increase domestic water consumption per capita; (2) improving water efficiency has a positive effect on mitigating water stress, but the population growth decreased the efficiency. It was concluded that much greater attention needs to be paid to water conservation in residential and living use to counter these unintended water management effects.

INTRODUCTION

Human survival and development cannot be separated from the exploitation and utilization of water resources. However, once the development and utilization of water resources continue to increase or even exceed the total amount of local water resources quantity, it leads to a significant strain on the local water resources—so called water stress. Water management is particularly important in the context of water stress mitigation. Water management involves a multi-criteria planning and decision-making process that thoroughly evaluates all aspects of the water utilization and cycle by considering collective impacts and interconnections with other management sectors.[1] Existing research and applications show that water supply and consumption are the primary factors affecting water stress worldwide, with numerous studies confirming adding water supply sources and increasing water efficiency to be the two main strategies for reducing water stress.[2–4] Water transfer refers to importing non-local water from a basin with abundant water resources to those in shortage.[5] Water efficiency is widely defined as the extent to which water resources contribute to economic growth, and it is quantified by the ratio of water consumption to the local Gross Domestic Product (GDP). And water stress can be mitigated effectively using multi-water management stratagems, with the aims of decreasing the exploitation and utilization of water resource within a certain space and result in a reduction of the degree of water resource development. Although worldwide water use is predicted to increase by 50% in developing countries and 18% in developed countries by 2035,[6] with non-traditional water source usage increasing through cross-basin water transfer,[7,8] desalination,[9,10] etc., improved water utilization efficiency through water-saving technology and recycled water[11,12] can reduce water demand. However, water stress has generally not been effectively alleviated. The inherent of water management in water stress is not simply to increase the water supply in the area with heavy water stress but also involves solving water demands.[13] Biswas (2008) discussed the various aspects that should be integrated into water management, which included the economic efficiency of water and water transfer projects. Scholars established the assessment of urban water resources management[14,15] and analyzed the transformation patterns regarding integrated water resources management of cities.[16] Based on this, this research attempts to quantify the effectiveness of water stress mitigation in respect of water management.

Cities have the strongest interactions with, and the most significant impact on, coupled human and natural systems[17] and are particularly dependent on water, with 60% of water tapped for use by people being consumed in cities.[18,19] As urbanization continues to develop, cities will continue to pose a significant challenge around using water resources.[20,21] Increasing water demands have forced the intensity of water resource development and utilization to increase and caused heavy water stress in cities, a widespread problem in many parts of the world.[2–4,22]

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As one of the 13 water-scarce countries, China has been facing an increasingly serious water shortage crisis and water stress for a long time[23,24] and has made extensive efforts to improve and mitigate issues around water stress.[25–29] The United Nations (UN) (2015)[30] in their development of the Sustainable Development Goals (SDGs) specified goal 6.4.2 on water stress to facilitate this challenge of increasing water demand, with the increasing interactions between human and natural systems and their effects. Scholars also focus on another solution to relieve water stress: cities conserving local water resources by importing water-intensive products instead of producing them locally—so-called virtual water.[4,31] How much water resources are saved by improving water efficiency and how much qualified water supply is added by purifying water quality have also been assessed in water mitigation solutions.[32]

Falkenmark defined the water resources less than the 1,000 m^3/person/year as experienced severe water shortage.[33,34] Currently, however, two-thirds of China's cities are facing severe water shortages,[35] and more than half face insufficient water supply for residents[36] from over-exploitation of water resources. For example, Beijing's 2017 per capita water resources were 161 m^3/person,[34] equating to less than a quarter of the severe water shortage standard (1,000 m^3/person).[37,38]

Previous studies have extensively examined the policy, technology, and assessment of water stress mitigation, attracting significant attention from scholars. In the policy for alleviating water stress, research has primarily focused on the status of water stress through perspectives of water supply infrastructure needs, departmental water use coordination, etc., making suggestions to policy-maker.[32,39,40] Moreover, from the technology perspective of water-saving, recycling water and seawater desalination[11,12,41] increase the available water quantity and mitigate the water stress. Scholars also concentrate on water stress assessment to evaluate water stress. By evaluating the water stress on a national scale, the developing nations are and will continue to affect water stress. By assessing freshwater scarcity, scholars pointed to two-thirds of the global population living under conditions of severe water stress.[42,43] Previous studies have called attention to the problem of increasing water stress and have sought to alleviate it through policies and technologies pathways. However, previous studies have not provided a satisfactory explanation for the ongoing increase in water stress, especially why the policy and technology for water stress mitigation are ineffective, which is not conducive to solving the problem of water stress mitigation. The human-led water management in cities frequently has significant effects on sustainable development and may have unforeseen results (Figure 1). An effective water management strategy is to use various stratagems with the expectation of mitigating water stress, and when the strategies are adopted, the actual result is a decrease in water stress. Once there is a gap between the expectation of mitigating water stress and actual results, we define it as unintended effects in this study.

In response, this study addressed these knowledge gaps by a three-step process. First, the indicators of water stress, efficiency, and the proportion of the consumption of non-local water by water transfer projects (ratio of water transferred, RTW) in 193 cities in China were calculated from 2010 to 2019 to investigate trends. The cities are divided into different eco-climate regions, population, economic sizes, and socioeconomic levels (Table S2). Second, we applied the Data Envelopment Analysis (DEA) model to analyze water efficiency in the utilization process, a reflection of whether achieving maximum economic growth entailed minimal water resources consumption.[44] Theil index for water stress inequality and domestic water consumption per capita was used to measure the awareness of water conservation. Based on these three indices, a water resources management effect index (WRMEI) was created to quantitatively evaluate the trends of water management and identify the effects. Third, we used the evidence found—that unintended effects and urbanization are two driving factors limiting water stress mitigation—in combination with spatial analyses to explore the implications for future water management strategies. The findings complement the existing literature, showing that water efficiency and transfer can mitigate water stress but have unintended effects between the expectation of water stress to be mitigated and the actual results of water stress increasing, providing evidence for the existence of unintended effects in water resources management, and emphasizes that much greater attention needs to be paid to solving unintended effects in the future. The unintended effects of water management in China are illustrated to show that the approach and results are tractable both across the country and globally.[45]

RESULTS

Character of water stress, efficiency, and transfer in Chinese cities

With improved water efficiency and transfer, water stress is increasing in Chinese cities. Water stress was measured by water resources development intensity (WDI index), whereas water efficiency was measured by water consumption per unit of GDP (WCG index). Water transfer was calculated as the ratio of water transferred (RTW index) from a different basin water source to water supply within a city. The formulas are presented in Equations 1, 2, and 3.

The results show that water stress experienced an increase from 2010 to 2019 in general, with a total 19.6% increase over the past 10 years (Figure 2A). By contrast, water efficiency improved by 142.4% over the past 10 years, and the ratio of transferred water improved to 2.6% over the past 10 years (Figures 2B and 2C).

For better understanding the characteristics of water stress mitigation in Chinese cities, we further evaluated the water stress, water efficiency, and water transferred in cities of different eco-climate regions, sizes, and socioeconomic levels.

Characteristics of water stress, efficiency, and transfer in different eco-climate regions

We divided cities into five different eco-climate regions: humid subtropical (SH), humid temperate (TA), temperate sub-humid (TSH), temperate arid (TA), and temperate/plateau semi-arid (TPA).

From the perspective of the five eco-climate regions, Figure 2A shows that water stress was consistent with the cities' natural endowment base. Water resources were scarcer in the arid area (TA region and TPA region), and the TA region had the highest water stress. The TPA region had the second-highest water stress, and the SH region had the lowest. In 2019, the water stress in the TA, TPA, and SH regions

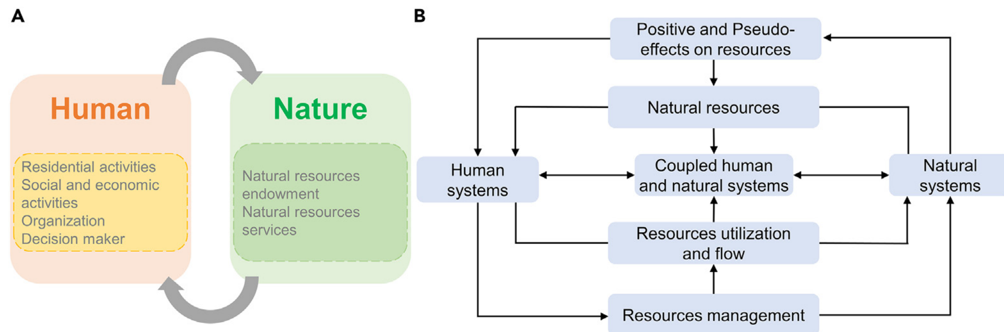

Figure 1. Water management in the water transfer system

(A) Coupled Human and Natural Systems (CHANS) is a functional whole composed of human and natural aspects in a certain space, with two major components: humans and nature.[70] The human component comprises residential, social, and economic activities, organizations, decision-makers, and other elements. The nature component consists of natural resources endowment, natural resources services, and other elements.

(B) Cities are Coupled Human and Natural Systems, with the latter providing resources to support human well-being; meanwhile, human activities in city systems manage resources, producing corresponding effects.

was 38.5%, 16.9%, and 4.8%, respectively. This implies that water resources endowment, the amount of local water resources quantity, plays a significant role in the degree of water stress. However, the TPA region, the only eco-climate region without water transfer, showed a decreasing trend in water stress, with a 39.4% decrease from 2010 to 2019. This result implies that although water resources endowment generates a baseline for cities' water stress, increasing of water resources endowment cannot result in a decrease of water stress in China.

In addition, water efficiency in all five eco-climate regions increased from 87.1% to 163.6% over the past 10 years. Moreover, except for the temperate/plateau semi-arid region, the other four regions transferred water to different degrees, with the ratio of transferred water ranging from 1.3% to 7.2% from 2010 to 2019. However, their water stress increase varies from 12.1% to 178.1% over the past 10 years. Both results from all the cities and eco-climate regions indicated increased water stress, despite improved water efficiency and the amount of transferred water in general. This result implies that although the water efficiency and transfer were improved, they did not result in a reduction of the WDI index in the cities.

Characteristics of water stress, efficiency, and transfer in different sizes and socioeconomic levels

Population growth, economic development, and socioeconomic improvement are urban development's three most important features. We further evaluated the water stress, water efficiency, and water transferred in cities of different sizes, economic and social development by population, GDP, and GDP per capita.

We divided cities into five different population sizes:[46] super cities (SU), megacities (ME), big cities (BI), medium cities (MD), and small cities (SM); four different economic sizes according to GDP: Class I, Class II, Class IV, and Class III, of which GDP was larger than 1,000, 500–1,000, and 50–500 and smaller than 50 billion CNY, respectively; and four different socioeconomic development levels according to GDP per capita (GDPPC): Class A, Class B, Class C, and Class D, of which GDPPC was larger than 110, 80–110, and 40–80 and smaller than 40,000 CNY.

Figure 2A shows that the degree of water stress of each population size was consistent with the population size, and the urban population showed a strong positive correlation with the WDI index (Figure 5B), indicating that the greater the population, the heavier the water stress. From 2010 to 2019, the WDI index was increasing in megacities, big cities, and medium cities while slightly decreasing in super cities from 63.9% to 63.4% over the past 10 years. The water stress in small cities has decreased by 61.7% from 2010 to 2019 because the population was decreased by 4.4%. The order of the WDI index in economically classified city sizes was as follows: Class I > Class II > Class IV > Class III. The water stress experienced an increase in all the economic sizes except Class IV. At the same time, GDP also had a significant positive correlation with the WDI index (Figure 5B). In addition, we clarified cities at different socioeconomic development levels. A higher socioeconomic development level resulted in heavier water stress (Figure 2A), and GDP per capita had a significant positive correlation with the WDI index (Figure 5B). Both the degree of water stress and the significant positive correlation of the WDI index imply the urbanization is a major driven force of water stress and the urban development is conducive to improving the water stress.

Figure 2B shows that the WCG index decreased from 2010 to 2019, reflecting that water efficiency experienced an increase in each city's size and level in the past 10 years. From the structure of the WCG index, GDP development has been taken into consideration. We further analyze the correlation between population, GDP per capita, and WCG index. The results show that the WCG index had a negative correlation with population from 2010 to 2019 and a negative correlation with GDP per capita in 2010, indicating that urbanization shapes water efficiency in Chinese cities.

In addition, larger city sizes and higher socioeconomic development levels show a larger RTW index, and population, GDP, and GDP per capita had a significant positive correlation with the RTW index. This indicates that cities with larger population/economic size and higher development levels rely more on non-local water resources. The trend of the RTW index of each city size and level has increased in the past 10 years, which implies the cities are increasingly dependent on non-local water (Figure 2C).

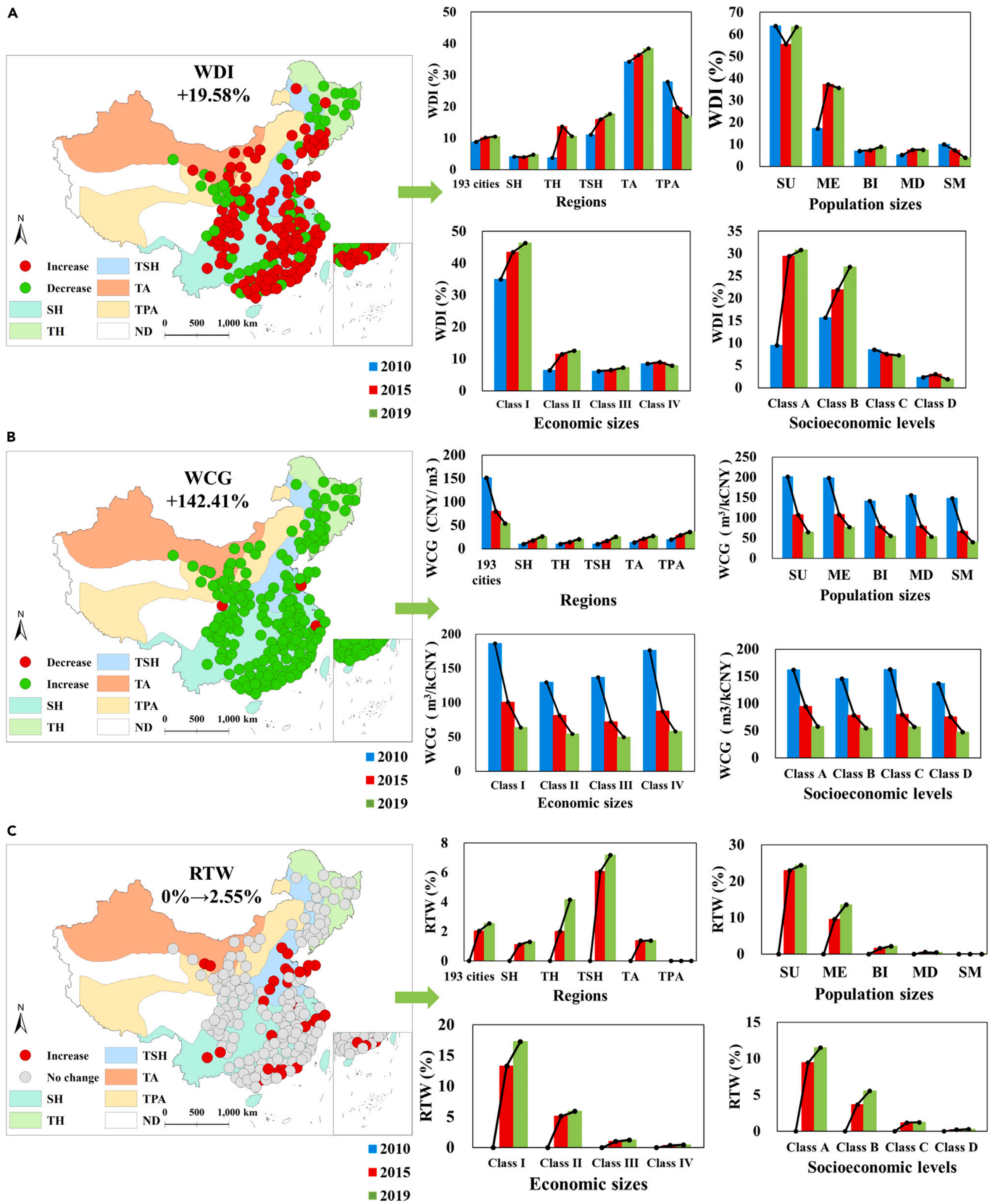

Figure 2. Trend of water stress, efficiency, and transfer

(A) Changes in water stress. Water stress increased by 19.6% over the past 10 years. ND denotes no data; the red and green circles represent an increase and a decrease in water stress, respectively.

Figure 2. *Continued*

(B) Changes in water efficiency. Water efficiency improved by 142.4% over the past 10 years. WCG index denotes water consumption per unit of GDP, and the reciprocal transformation is shown; the larger the WCG index value, the higher the economic efficiency.

(C) Changes in the ratio of transferred water. RTW index, the ratio of transferred water, increased to 2.6% over the past 10 years: the larger the RTW index, the larger the proportion of water transferred by the city.

In conclusion, the characteristics of water stress, water efficiency, and water transfer of cities in different eco-climate regions, city sizes, and levels show water stress was increased by urbanization and was consistent with the water resources endowment. Meanwhile, urbanization can significantly improve water efficiency and use more transferred water. However, the water stress was not mitigated under these two means. There are two potential explanations for the increasing water stress. First, improving water efficiency and importing water may not be effective strategies for water stress mitigation. Second, the rapid pace of urbanization may surpass the available water resources in cities and exacerbate the water stress. We will conduct a further analysis of these factors.

Improved water efficiency can reduce water stress

The results show that the water stress reflects by WDI index from 193 cities were positively correlated with water efficiency reflects by WCG index (the smaller WCG index, the smaller WDI index) (Figure 3). In the eco-climate regions, water stress index and water efficiency index were also negatively correlated in the SH, THS, and TPA regions during 2010–2019, as was the TA region in 2010 (Figure 3A). And from the perspective of the nine city sizes and four socioeconomic levels, four types of cities had a negative correlation with water stress and efficiency during 2010–2019, as did five types of cities in most years (Figures 3B–3D): this indicates that cities with a higher water efficiency tend to have a lower water stress.

The cities' water stress was positively correlated with water transfer. Based on the eco-climate regions division, all regions have transferred water from other regions except the temperate/plateau semi-arid region. From 2010 to 2019, the city size of Class I, city level at Class A, and eco-climate region of SH had a significantly positive correlation between water stress and transfer, the correlation increasing gradually in the super city, mega city, TA, and TSH regions, and a positive correlation in 2010 in the small city (Figure 3B). This indicates that the cities with a higher water stress relied more on non-local water sources.

We further analyze whether water resources endowment impacts the destination of water transfer. RTW index and water resources were negatively correlated for all the cities in 2015 and 2019 (Figure 4): the greater the stress of water resources, the more the water was transferred. Therefore, the results indicate that the greater the water stress, the higher the ratio of water transfer, revealing that the management of transferred water was based on demand orientation in the cities and delivered water to those with scarce water resources and greater water stress. In China, water resources availability greatly increases from North to South, whereas the water demand increases from East to West (See Figure S2). The inequality of water between the available and demand may explain the exacerbation of water shortages.[31] Water transfer can improve the pattern of water resources available between north and south inequality over the space.

In this section, we confirm that improving water efficiency and increasing water transfer are two effective strategies in water stress mitigation. Improved water efficiency reduces the water stress index, and water was transferred to cities with a higher water stress. However, the results in Figure 2 indicate that water stress in cities generally increased over the last decade. This is a surprising result, as it was expected that increased water use efficiency and water transfers would have resulted in an overall decrease in the water stress and WDI index. The results suggest that there may be unintended effects between actual results and expectations in water management strategies that have negated the attempts to improve water efficiency and import water to mitigate cities' water stress.

Unintended effects cause the gap between the actual results and expectations of water management measures and water stress mitigation

We leveraged the water efficiency in the utilization process (WUE index), awareness of water conservation (WCP index), and inequality in water stress (WST) to evaluate the water management effects (for the results of city levels, see Table S3). Water transfer projects aim to alleviate water shortage, and the intention of transferring water in China is to prioritize the supplementing of domestic water.[47] Figure 5A shows that the SH region had a significantly positive correlation between RTW index and domestic water consumption per capita (WCP index), as were in the TH region in 2010 and 2015, the city level at Class A in 2010, which means that the more the water was transferred, the more the domestic water consumption per capita. This implies that water resources were not utilized sparingly in the receiving region and suitably explains why water transfer has not mitigated water stress in reality.

The calculation formulae are presented in Equations 4, 5, 6, 7, 8, 9, and 10, and Figure 5B shows that the WUE index decreased by 22.9% over the past 10 years. This is because the capital and population growth were considered in the water efficiency utilization process, which indicates that capital and population growth offsets the gains in water efficiency in the economic aspect of reducing the water stress.

Both Figures 4B and 4C suggest that urban China has combined unintended effects, causing a lack of water conservation awareness and an increase in residents' water use demands, resulting in a water management gap between expectation and reality. Therefore, although water resources management and water stress mitigation strategies have been implemented, water stress has not been mitigated. These unintended effects of water resources management are a major omission in current water resources management strategies.

Figure 5B shows that, due to the water transfer project, the WST index for water stress inequality decreased by 17.1% from 2010 to 2019. These positive effects of water management and the unintended effects were offset from the point of water stress inequality.

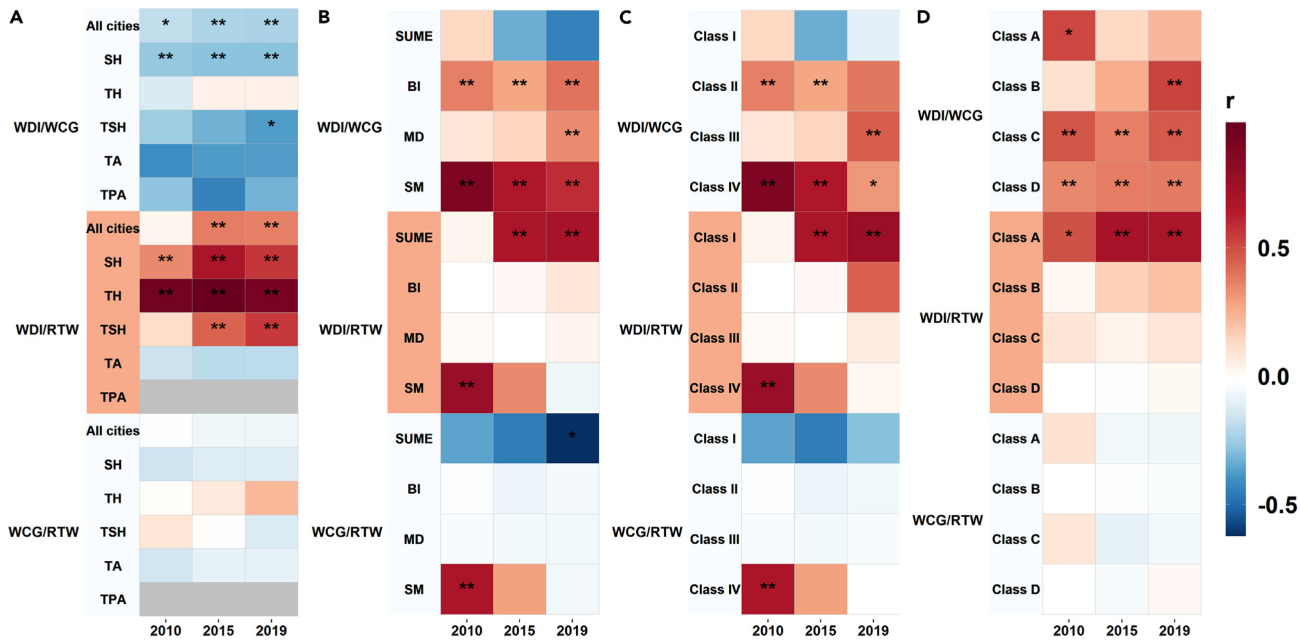

Figure 3. Correlation coefficients between water stress, water efficiency, and water transfer from 2010 to 2019

(A) The heatmap of the correlation coefficients for all the cities and cities of different eco-climate regions. The color denotes the correlation level.

(B) The heatmap of the correlation coefficients for all the cities and cities of different population sizes. The color denotes the correlation level.

(C) The heatmap of the correlation coefficients for all the cities and cities of different economic sizes. The color denotes the correlation level.

(D) The heatmap of the correlation coefficients for all the cities and cities of different socioeconomic levels. The color denotes the correlation level. *$p < 0.05$, **$p < 0.01$.

In addition, the WRMEI index was used to evaluate the trend of water management effect, and the result shows a decrease in WRMEI index, indicating the effects of water management in the past 10 years was ineffective. In conclusion, improving water efficiency and the water transfer plays a role in mitigating water stress, but the positive gains will be largely offset by the unintended effects caused by human activities in water utilization.

Water resources endowment supports urban economic development

Urban development is inseparable from the use of water resources.[48] Based on the aforementioned results, we point out that the degree of water stress was consistent with natural endowment: the TA region, which has the highest water stress, followed by TPA region. In addition, from the index structure of water factors, we found that while under constant water supply conditions, the relationship between WDI index, WCG index, and WCP index refers to the relationship between water resources, GDP, and population to some extent. The correlation analysis results show a positive correlation between water resources and GDP in 2015 and 2019 (Figure 5A). More water resources and a higher GDP indicate the important supporting role of water resource endowment in urban economic development. In addition, studies have revealed that China has promoted economic growth in water-receiving regions through the transfer of water. This allows the country to increase GDP by USD 400 billion annually, supporting our results that water resources play a key role in supporting urban development.[49] Our results therefore provide evidence that water resources still play a crucial role in urban economic development.

We developed a simple scenario to evaluate the impact of different water resources management strategies on water quantity, stress, and GDP. By evaluating 18 water transfer projects in China, scholars found water transfer projects have the potential to increase China's annual GDP by 4%.[49] Due to limited data availability, we chose to focus on the South-North Water Transfer Project to evaluate GDP changes resulting from water transfer. The South-North Water Transfer Project is planned to ultimately transfer 27.8 billion m^3 per annum of water in 2030 through the East and the Middle Route.[50,74] Based on the city-level data we obtained, 1,928 million m3 of water will be transferred to Beijing, and 2,973 m^3 of water will be transferred to Tianjin in 2030.[51] The water transferred is expected to contribute to an additional GDP increase in 2030 by USD 2224.0, 154.2, and 237.8 million in China, Beijing, and Tianjin, respectively. In addition, the Chinese government proposed a target of a 16% increase in water efficiency (the value of the WCG index decreased by 16%) by 2025 in the latest five-year plan (2021–2025) document.[52] Taking a 16% increase in water efficiency as a benchmark, we assumed a 16% increase in water efficiency for 193 cities from 2019 and chose to use the same GDP in 2030 as in 2019. This ensures that our study focused on the impact of water efficiency on water quantity and water stress (WDI index). The result is a 6.0 billion m^3 decrease in water consumption. Thus, the WDI index is 8.6%, a decrease of 19.1% from 2019 to 2025. We also established an estimating framework for the impact of water transfer on GDP. The results show that water transfer brought a 2.0% GDP growth to the cities on the East Route of The South-North Water Transfer Project in 2019. We assumed a 1%

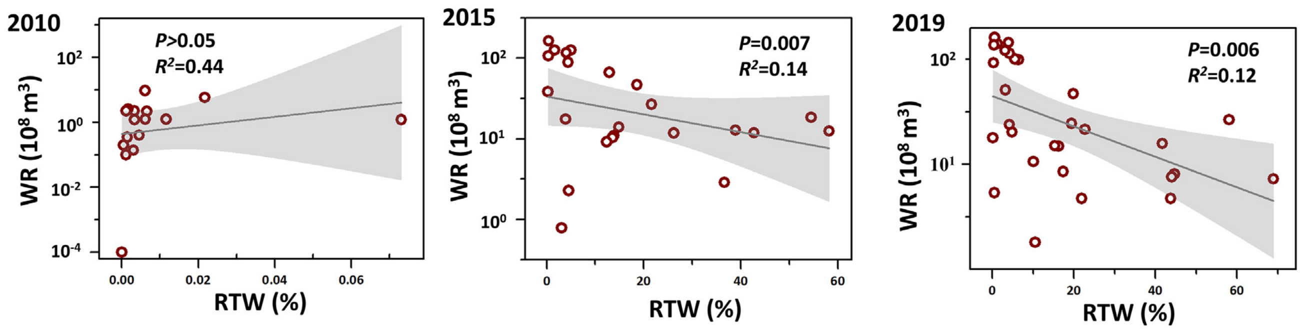

Figure 4. Correlation coefficients between water transfer and water resources from 2010 to 2019

The management of transferred water is based on demand orientation. The relationship between water resources and transferred water, where the gray line is the linear fitting of results. The circle indicates the sample cities. *$p < 0.05$, **$p < 0.01$.

increase in transferred water volume in 2019; not only would the water quantity in the receiving cities increase by 1%, but this transferred water would also contribute to an increase in GDP by 2.2%.

Urbanization exacerbates increasing water stress

China's water transfer project is based on demand orientation and attempts to alleviate water shortages and excessive water stress. Our research results show that improved water efficiency and increased transfer of water can reduce water stress (Figure 5). Theil indices show that the inequality of water stress had been mitigated thanks to water transfer projects. However, due to the unintended effects of water management, water stress index in the cities increased by 19.6% over the past 10 years. This research results show that a larger city size and higher development level resulted in heavier water stress (Figure 2A) and confirms that urbanization increases the cities' water stress (Figure 6B). Additionally, we point out that water resources support urban economic development, suggesting that the increase of future water stress may be an inevitable result, with the urgency for urbanization still being one of the main trends in developing countries.[53]

Population growth and socioeconomic development have led to largely unsustainable water use worldwide,[19] especially in urban areas.[20] For many developing countries, human activities related to urbanization are the main factor causing increases in water stress.[43] Our results emphasize that urban development remains another main influencing factor of China's continuously increasing water stress. Moreover, the geographical inequality between freshwater demand and available freshwater resources, and the large amount of water demand caused by the desire for urbanization, are other drivers increasing water stress.

In conclusion, rich water resources underpin economic development, and the resulting population growth in cities forces water stress, which has not been sufficiently mitigated. We emphasize that much greater attention needs to be paid to water conservation in residential areas to remedy these unintended effects in water management.

DISCUSSION

Building on previous water management strategies in Chinese cities, this study expands knowledge in the following four fundamental aspects. First, although cities import water to provide additional water sources and improve water efficiency, we show that, in terms of WDI index, the trend was rising and water stress has not been mitigated (Figure 2). Second, we analyzed the relationship between water stress, water efficiency, and water transfer to identify if water stress can be reduced by improving water efficacy and water transfer. And we find water was imported into cities with heavy water stress. Meanwhile, gains in water efficiency was shown to mitigate the cities' water stress (Figure 3). This finding enables us to verify that water management strategies can mitigate water stress, but there was a gap between actual results and expectations. Third, WRMEI was created in this study to quantitatively evaluate water management's trends in the cities. We discovered that the unintended effects caused by human behavior create a gap between water management results in reality and expectation, that is, the expectation of reducing water stress contrasts with the reality of water stress increasing (Figure 5). The finding of unintended effects caused by human behavior in water resources management needs to be noticed by decision-makers who relate to water management both nationally and internationally. Fourth, it was shown that, combined with the great use of resources for economic development and the desire for urbanization (Figure 6), water stress has not been effectively mitigated due to the presence of unintended effects. Urban development affects the utilization of natural resources.[54] This finding of the significant results of unintended effects and human activity on increased water stress enables this research to provide tailor-made water management suggestions for water stress mitigation, as is further discussed later.

Unintended effects cannot be ignored in future water management

The modifying unintended effects urgently need to be taken into account. Unintended effects are ignored in previous strategies of water management. Our results show that enhancing the awareness of water conservation and improving water efficiency in the utilization process were necessary to eliminate unintended effects. In addition, improving water efficiency in the utilization process is more suited to solve the water stress dilemma of Chinese cities than water transfer.

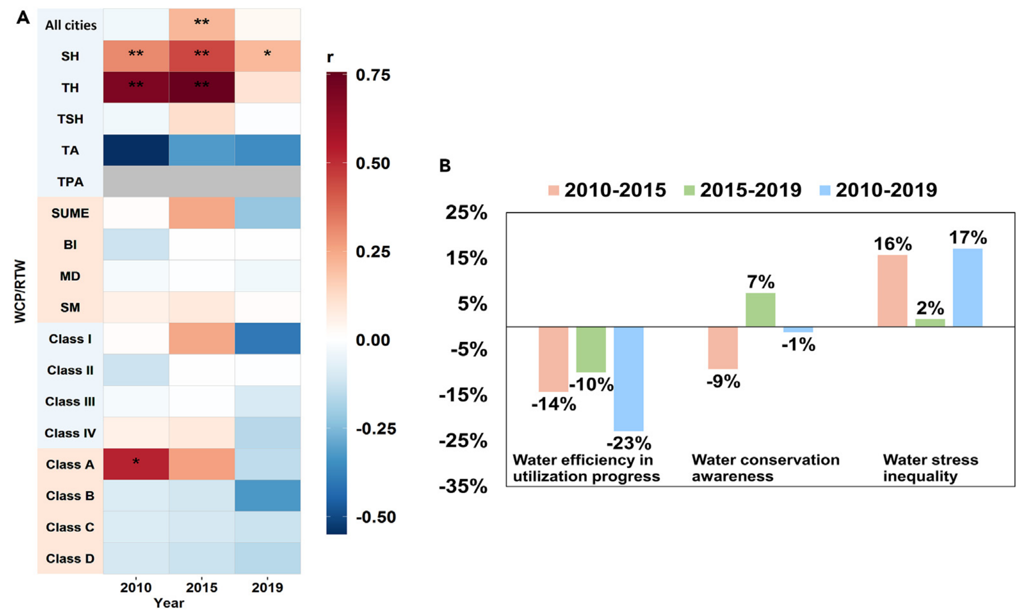

Figure 5. Patterns of unintended effects in water resources management

(A) The heatmap shows the correlation coefficients between RTW index and WCP index for all the cities and cities of different eco-climate regions, sizes, socioeconomic levels. The color denotes the correlation level. *$p < 0.05$, **$p < 0.01$.

(B) The trends of water efficiency in the utilization process, awareness of water conservation, and inequality in water stress from 2010 to 2019.

Groundwater is classified into two types: renewable and non-renewable. Scholars defined the non-renewable groundwater as the groundwater with mean renewal times surpassing human timescales (>100 years). In other words, when the groundwater is taken out of storage, it will likely not be replenished on human timescales; the groundwater resources are considered as non-renewable resources. Groundwater depletion occurs when the multi-annual withdrawal of groundwater exceeds average annual replenishment, leading to a persistent decline in groundwater levels and reduction of groundwater volumes, particularly occurring during the non-renewable groundwater withdrawal.[55,56] Studies have reported the groundwater depletion is threatening many cities globally,[57–59] and the cities in the North China Plain (NCP) have also been threatened by groundwater depletion and suffered severe water shortages during the past 20 years.[38,60,61] Water transfer projects have been pointed out to contribute to the recovery of groundwater depletion and stabilizing groundwater levels in NCP.[62,63] In addition, using transferred water reduces the energy consumption on groundwater exploitation by reducing the groundwater pumping.[64] Furthermore, the river is one of the dominant components in the water supply. Human water demands cannot use all the water resources in the river because the river also has environmental water demands to maintain river ecosystem health. Otherwise, it will result in water scarcity in the river. Scholars using monthly data assessed the water scarcity of rivers. They found that out of 12 months of the year, 28%–60% of the population was affected by water scarcity globally, and 22%–58% of land area in north China was under water scarcity.[65,66] Water transfer manages water quantity from the perspective of the basin. It impacts the water supply of half of the sub-basins and benefits more than a half of the national population in China.[67] Scholars pointed out that water management in China has been dominated by engineering projects (i.e., water transferred) to satisfy water demands.[64] Water transfer project is increasingly being promoted and required in China, due to such a great contribution of water transfer projects to groundwater recharge. Furthermore, in this study, the unintended effects in transferred-water-receiving cities: both the amount of domestic and total water consumed per person increases with the ratio of transferred water. This surprising finding is a scientific foretaste of the future water management in China: cities, particularly the transferred-water-receiving cities, can use water resources more sparingly and improve water efficiency. Existing studies have pointed out that water transfer does not directly impact the change of GDP.[68] However, high price of transferred water is an issue in water-receiving cities. To cover construction and maintenance costs of the water transfer projects, users have to pay higher prices for the water, increasing economic pressures on local governments, factories, and residents. Improved water efficiency was significantly related to mitigating water stress (Figure 3): thus, vigorously promoting water-saving technology and increasing residents' awareness of water saving are needed to improve local water efficiency, especially water efficiency in the utilization process, as an effective measure to mitigate the cities' increasing water stress. Many cities have also confirmed that improving water use efficiency through water-saving measures can effectively reduce water consumption by approximately 20%–60%.[69] Thus, we emphasize more attention should be paid to the water efficiency improved in cities.

Future water resource management suggestions

According to these results, human activities were identified as the main factor causing water management unintended effects and determining the extent of water stress deterioration in the cities. Therefore, to better mitigate the water stress of urban China, we propose a

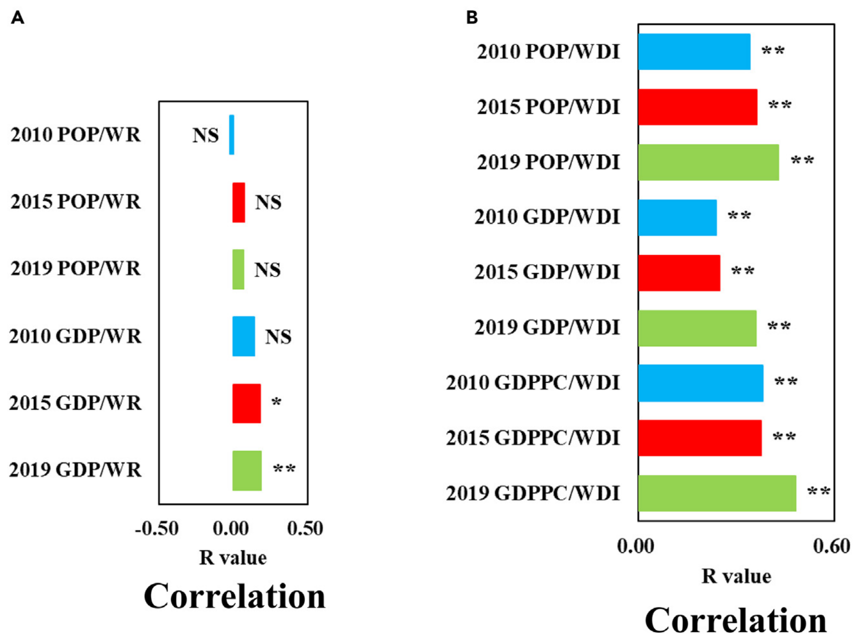

Figure 6. Cause of the rise in water stress

(A) Contribution of water resources endowment to urban economic development. POP, population; WR, water resources. The results show that GDP and water resources were gradually and positively correlated from 2010 to 2019.

(B) Urbanization had a strong impact on WDI index. The results show that population growth, economic development, socioeconomic improvement, and WDI index always showed a significant positive correlation during the study period. GDPPC: GDP per capita represents cities' socioeconomic level. $^{*}p < 0.05$, $^{**}p < 0.01$.

city-specific list that will facilitate residents and governments to understand their water resource utilization situation and adopt suitable implementation strategies. Based on the 2019 results, we list eight cities whose values of WDI index, WCG index, WCP index, and RTW index were in the last quarter among 193 cities, with 12 cities with an RTW index = 0% having other index values listed in the same quarter (See Tables S6 and S7). Cities needing measures to ameliorate water utilization patterns should do so urgently. Cities with significant differences in urban water utilization patterns under similar natural resource endowments have an optimization potential.

Using ArcGIS 10.5, the univariate spatial autocorrelation analysis of the four indices (WDI index, WCG index, WCP index, and RTW index) was carried out. Twelve "HL cities" were identified, meaning that, under similar natural resource endowments, they have poor water utilization (Table S8). Cities can learn from the utilization mode of the surrounding areas to alleviate water stress. Furthermore, the GeoDA 1.18.0 software was used to conduct bivariate spatial autocorrelation analysis of the three urbanization indices and the four water utilization indices (see Figure S3–S10). The results revealed five high and three low urbanized cities with a large water resources consumption level (see Tables S9 and S10). Finally, we eliminate the duplicate cities of those three types and obtain a 30 specific-cities optimization list of urban water utilization patterns (see Tables S4 and S5).

Limitations of the study

Notably, the quantity of water resources exhibits seasonal fluctuations; the quantity of groundwater and surface water can vary across different seasons and months. The human water demand in the city is a critical factor in the evaluation and assessment of water stress and water management. To improve the future water management effects, a monthly water stress assessment could be applied when the prolonged monthly water demand data can be accessed at the city level. Based on this, water supply sources and water consumption types and the ratio of transferred water in different consumption types can be clarified on how urban water stress and water transfer impact the scarcity of different water sources and provide more tailor-made suggestions in future water management design. The volume of water transfer in cities can be accessed. However, we lack specific information on the water delivery routes (each city receiving water from which cities and importing to which cities). Thus, the evaluation of the economic impact of water transferred at the city level cannot be totally estimated. However, once the necessary data become available, the evaluation framework proposed in this study for the impact of water transfer on GDP growth can be estimated.

Conclusion

By calculating the water stress, efficiency, and transfer and using WRMEI to quantify the trends of water management effects of 193 Chinese cities from 2010 to 2019, our study found that the current water resources management strategies were affected by unintended effects caused by human behavior in two respects. First, water resources were not utilized sparingly in the receiving cities; the amount of both domestic and total water consumed per person increases when the RTW index (transferred water becomes a larger percentage of available water supply) increases. Second, improving water efficiency has a positive effect on mitigating water stress but was decreased by the population. Furthermore, we confirmed that water resources are important in supporting urbanization and the neglected existence of unintended effects in human behavior—lack of water-saving consciousness and increased residents' water use demands due to urbanization, resulting in increased water stress. This study emphasizes that much greater attention needs to be paid to unintended effects. In addition, we provide suggestions aimed at improving water efficiency, especially by promoting efficiency in residential water use, which is significant for water stress mitigation. Finally, it should be pointed out that although the study takes China as an example, the finding of the unintended effects in water management has worldwide significance.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.109195.

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AUTHOR CONTRIBUTIONS

Y.L. and Z.O. designed research. Y.L., B.H., F.L., C.G., and Z.O. performed research. Y.L. conducted the analysis and wrote the paper. Y.L. and C.G. drew the figures. Y.L., Z.O., C.J., and X.Z. reviewed the paper, exchanged ideas, and prepared the final version of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. Chang, I.S., Zhao, M., Chen, Y., Guo, X., Zhu, Y., Wu, J., and Yuan, T. (2020). Evaluation on the integrated water resources management in China's major cities – Based on City Blueprint® Approach. J. Clean. Prod. *262*, 121410. https://doi.org/10.1016/j.jclepro.2020.121410.
2. Gleeson, T., Wang-Erlandsson, L., Zipper, S.C., Porkka, M., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S.E., Piemontese, L., Gordon, L.J., et al. (2020). The Water Planetary Boundary: Interrogation and Revision. Cell Press *2*, 223–234. https://doi.org/10.1016/j.oneear.2020.02.009.
3. Zhao, X., Liu, J., Yang, H., Duarte, R., Tillotson, M.R., and Hubacek, K. (2016). Burden shifting of water quantity and quality stress from megacity Shanghai. Water Resour. Res. *52*, 6916–6927. https://doi.org/10.1002/2016WR018595.
4. Liu, X., Du, H., Zhang, Z., Crittenden, J.C., Lahr, M.L., Moreno-Cruz, J., Guan, D., Mi, Z., and Zuo, J. (2019). Can virtual water trade save water resources? Water Res. *163*, 114848. https://doi.org/10.1016/j.watres.2019.07.015.
5. Zhuang, W. (2016). Eco-environmental impact of inter-basin water transfer projects: a review. Environ. Sci. Pollut. Res. Int. *23*, 12867–12879. https://doi.org/10.1007/s11356-016-6854-3.
6. (2007). Water: A Shared Responsibility – The United Nations World Water Development

Report 2. Dev. Pract. *17*, 309–311. https://doi.org/10.1080/09614520701197333.
7. Madani, K., and Lund, J.R. (2012). California's Sacramento–San Joaquin Delta Conflict: From Cooperation to Chicken. J. Water Resour. Plan. Manag. *138*, 90–99. https://doi.org/10.1061/(asce)wr.1943-5452.0000164.
8. Gallardo, B., and Aldridge, D.C. (2018). Inter-basin water transfers and the expansion of aquatic invasive species. Water Res. *143*, 282–291. https://doi.org/10.1016/j.watres.2018.06.056.
9. Sauvet-Goichon, B. (2007). Ashkelon desalination plant - A successful challenge. Desalination *203*, 75–81. https://doi.org/10.1016/j.desal.2006.03.525.
10. Greenlee, L.F., Lawler, D.F., Freeman, B.D., Marrot, B., and Moulin, P. (2009). Reverse Osmosis Desalination: Water Sources, Technology, and Today's Challenges (Elsevier Ltd). https://doi.org/10.1016/j.watres.2009.03.010.
11. Ghimire, S.R., Johnston, J.M., Ingwersen, W.W., and Sojka, S. (2017). Life cycle assessment of a commercial rainwater harvesting system compared with a municipal water supply system. J. Clean. Prod. *151*, 74–86. https://doi.org/10.1016/j.jclepro.2017.02.025.
12. Lyu, S., Chen, W., Zhang, W., Fan, Y., and Jiao, W. (2016). Wastewater reclamation and reuse in China: Opportunities and challenges. Chin. Acad. Sci. https://doi.org/10.1016/j.jes.2015.11.012.
13. Grigg, N.S. (2008). Integrated water resources management: Balancing views and improving practice. Water Int. *33*, 279–292. https://doi.org/10.1080/02508060802272820.
14. Grison, C., Koop, S., Eisenreich, S., Hofman, J., Chang, I.S., Wu, J., Savic, D., and van Leeuwen, K. (2023). Integrated Water Resources Management in Cities in the World: Global Challenges. Water Resour. Manage. *37*, 2787–2803. https://doi.org/10.1007/s11269-023-03475-3.
15. Biswas, A.K. (2008). Integrated water resources management: Is it working? Int. J. Water Resour. Dev. *24*, 5–22. https://doi.org/10.1080/07900620701871718.
16. Koop, S.H., Grison, C., Eisenreich, S.J., Hofman, J., and van Leeuwen, K. (2022). Integrated water resources management in cities in the world: Global solutions. Sustain. Cities Soc. *86*, 104137. https://doi.org/10.1016/j.scs.2022.104137.
17. Liu, J., Dietz, T., Carpenter, S.R., Folke, C., Alberti, M., Redman, C.L., Schneider, S.H., Ostrom, E., Pell, A.N., Lubchenco, J., et al. (2007). Coupled human and natural systems. AMBIO: A J. Hum. Environ. *36*, 639–649. https://doi.org/10.1579/0044-7447(2007)36[639:CHANS]2.0.CO;2.
18. Richter, B.D., Blount, M.E., Bottorff, C., Brooks, H.E., Demmerle, A., Gardner, B.L., Herrmann, H., Kremer, M., Kuehn, T.J., Kulow, E., et al. (2018). THE PERPETUAL NEED FOR SAFE WATER PRESENTS COMMUNITIES AND UTILITIES WITH 21ST-CENTURY CHALLENGES; A RECENTLY DEVELOPED SERIES OF INDICATORS CAN HELP IN ESTABLISHING AND MONITORING WATER SUSTAINABILITY EFFORTS. Feature Article Assessing the Sustainability of Urban Water Supply Systems.
19. Nazemi, A., and Madani, K. (2018). Urban Water Security: Emerging Discussion and Remaining Challenges (Elsevier Ltd). https://doi.org/10.1016/j.scs.2017.09.011.
20. Kontokosta, C.E., and Jain, R.K. (2015). Modeling the determinants of large-scale building water use: Implications for data-driven urban sustainability policy. Sustain. Cities Soc. *18*, 44–55. https://doi.org/10.1016/j.scs.2015.05.007.
21. Obianyo, J.I. (2019). Effect of salinity on evaporation and the water cycle. Emerg. Sci. J. *3*, 255–262. https://doi.org/10.28991/esj-2019-01188.
22. Nations, U., of Economic, D., Affairs, S., and Division, P. (2018). World Urbanization Prospects The 2018 Revision.
23. Liu, J., Yang, H., Gosling, S.N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y., Zhang, X., Zheng, C., et al. (2017). Water Scarcity Assessments in the Past, Present, and Future (John Wiley and Sons Inc). https://doi.org/10.1002/2016EF000518.
24. Chapagain, A.K., and Hoekstra, A.Y. (2008). The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. Water Int. *33*, 19–32. https://doi.org/10.1080/02508060801927812.
25. Deines, J.M., Liu, X., and Liu, J. (2016). Telecoupling in urban water systems: an examination of Beijing's imported water supply. Water Int. *41*, 251–270. https://doi.org/10.1080/02508060.2015.1113485.
26. Zhang, Q. (2009). The South-to-North Water Transfer Project of China: Environmental implications and monitoring strategy. J. Am. Water Resour. Assoc. *45*, 1238–1247. https://doi.org/10.1111/j.1752-1688.2009.00357.x.
27. Liu, J., Zhao, X., Yang, H., Liu, Q., Xiao, H., and Cheng, G. (2018). Assessing China's "developing a water-saving society" policy at a river basin level: A structural decomposition analysis approach. J. Clean. Prod. *190*, 799–808. https://doi.org/10.1016/j.jclepro.2018.04.194.
28. Zhang, C., Wu, Y., and Yu, Y. (2020). Spatial decomposition analysis of water intensity in China. Socioecon. Plann. Sci. *69*, 100680. https://doi.org/10.1016/j.seps.2019.01.002.
29. Du, M., Liao, L., Wang, B., and Chen, Z. (2021). Evaluating the effectiveness of the water-saving society construction in China: A quasi-natural experiment. J. Environ. Manage. *277*, 111394. https://doi.org/10.1016/j.jenvman.2020.111394.
30. Org, S.U. TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT UNITED NATIONS UNITED NATIONS TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT.
31. Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., and Hubacek, K. (2015). Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. USA *112*, 1031–1035. https://doi.org/10.1073/pnas.1404130112.
32. Ma, T., Sun, S., Fu, G., Hall, J.W., Ni, Y., He, L., Yi, J., Zhao, N., Du, Y., Pei, T., et al. (2020). Pollution exacerbates China's water scarcity and its regional inequality. Nat. Commun. *11*, 650. https://doi.org/10.1038/s41467-020-14532-5.
33. Falkenmark, M., Lundqvist, J., and Widstrand, C. (1989). Macro-scale water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development. Nat. Resour. Forum *13*, 258–267. https://doi.org/10.1111/j.1477-8947.1989.tb00348.x.
34. Zhao, Y., Wang, Y., and Wang, Y. (2021). Comprehensive evaluation and influencing factors of urban agglomeration water resources carrying capacity. J. Clean. Prod. *288*, 125097. https://doi.org/10.1016/j.jclepro.2020.125097.
35. He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J., and Bryan, B.A. (2021). Future global urban water scarcity and potential solutions. Nat. Commun. *12*, 4667. https://doi.org/10.1038/s41467-021-25026-3.
36. Liu, J., and Raven, P.H. (2010). China's environmental challenges and implications for the world. Crit. Rev. Environ. Sci. Technol. *40*, 823–851. https://doi.org/10.1080/10643389.2010.502645.
37. Zhu, L., Gong, H., Li, X., Wang, R., Chen, B., Dai, Z., and Teatini, P. (2015). Land subsidence due to groundwater withdrawal in the northern Beijing plain, China. Eng. Geol. *193*, 243–255. https://doi.org/10.1016/j.enggeo.2015.04.020.
38. Feng, W., Zhong, M., Lemoine, J.M., Biancale, R., Hsu, H.T., and Xia, J. (2013). Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements. Water Resour. Res. *49*, 2110–2118. https://doi.org/10.1002/wrcr.20192.
39. Gao, X., Schlosser, C.A., Fant, C., and Strzepek, K. (2018). The impact of climate change policy on the risk of water stress in southern and eastern Asia. Environ. Res. Lett. *13*, 064039. https://doi.org/10.1088/1748-9326/aaca9e.
40. Hamdy, A., Ragab, R., and Scarascia-Mugnozza, E. (2003). Coping with water scarcity: Water saving and increasing water productivity. Irrigat. Drain. *52*, 3–20. https://doi.org/10.1002/ird.73.
41. Elimelech, M., and Phillip, W.A. (2011). The Future of Seawater Desalination: Energy, Technology, and the Environment.
42. Mekonnen, M.M., and Hoekstra, A.Y. (2016). Sustainability: Four billion people facing severe water scarcity. Sci. Adv. *2*, e1500323. https://doi.org/10.1126/sciadv.1500323.
43. Schlosser, C.A., Strzepek, K., Gao, X., Fant, C., Blanc, É., Paltsev, S., Jacoby, H., Reilly, J., and Gueneau, A. (2014). The future of global water stress: An integrated assessment. Earth's Future *2*, 341–361. https://doi.org/10.1002/2014ef000238.
44. Wei, J., Lei, Y., Yao, H., Ge, J., Wu, S., and Liu, L. (2021). Estimation and influencing factors of agricultural water efficiency in the Yellow River basin, China. J. Clean. Prod. *308*, 127249. https://doi.org/10.1016/j.jclepro.2021.127249.
45. Liu, J., Hull, V., Batistella, M., deFries, R., Dietz, T., Fu, F., Hertel, T.W., Izaurralde, R.C., Lambin, E.F., Li, S., et al. (2013). Framing sustainability in a telecoupled world. Ecol. Soc. *18*, art26. https://doi.org/10.5751/ES-05873-180226.
46. State Council, 2014. In: State Council (Ed.), The Notice Concerning the Adjustment on Classification Standards of City Scale. Beijing.
47. Dong, Z., and Wang, J. (2011). Quantitative standard of eco-compensation for the water source area in the middle route of the South-to-North Water Transfer Project in China. Front. Environ. Sci. Eng. China *5*, 459–473. https://doi.org/10.1007/s11783-010-0288-9.
48. Kaushal, S.S., McDowell, W.H., Wollheim, W.M., Johnson, T.A.N., Mayer, P.M., Belt, K.T., and Penninov, M.J. (2015). Urban evolution: The role of water. MDPI AG *7*, 4063–4087. https://doi.org/10.3390/w7084063.

49. Yu, M., Wang, C., Liu, Y., Olsson, G., and Wang, C. (2018). Sustainability of mega water diversion projects: Experience and lessons from China. Sci. Total Environ. *619–620*, 721–731. https://doi.org/10.1016/j.scitotenv.2017.11.006.
50. Changjiang Water Resources Commission of The Ministry of Water Resources (2001). The Plan of Middle Route of the South-north Water Transfer Project (China Water Power Press).
51. Liu, J., Zang, C., Tian, S., Liu, J., Yang, H., Jia, S., You, L., Liu, B., and Zhang, M. (2013). Water conservancy projects in China: Achievements, challenges and way forward. Global Environ. Change *23*, 633–643. https://doi.org/10.1016/j.gloenvcha.2013.02.002.
52. (2021). National Development and Reform Commission: Notice of the National Development and Reform Commission and other departments on printing and distributing the "14th five year plan for building a water-saving society". https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202111/t20211108_1303414_ext.html.
53. Cohen, B. (2004). Urban growth in developing countries: A review of current trends and a caution regarding existing forecasts. World Dev. *32*, 23–51. https://doi.org/10.1016/j.worlddev.2003.04.008.
54. Liu, Y., Lu, F., Xian, C., and Ouyang, Z. (2023). Urban development and resource endowments shape natural resource utilization efficiency in Chinese cities. J. Environ. Sci. *126*, 806–816. https://doi.org/10.1016/j.jes.2022.03.025.
55. Bierkens, M.F.P., and Wada, Y. (2019). Non-renewable Groundwater Use and Groundwater Depletion: A Review (Institute of Physics Publishing). https://doi.org/10.1088/1748-9326/ab1a5f.
56. Edmunds, W.M. Renewable and Non-renewable Groundwater in Semi-arid and Arid Regions.
57. Richey, A.S., Thomas, B.F., Lo, M.H., Reager, J.T., Famiglietti, J.S., Voss, K., Swenson, S., and Rodell, M. (2015). Quantifying renewable groundwater stress with GRACE. Water Resour. Res. *51*, 5217–5238. https://doi.org/10.1002/2015WR017349.
58. Long, D., Pan, Y., Zhou, J., Chen, Y., Hou, X., Hong, Y., Scanlon, B.R., and Longuevergne, L. (2017). Global analysis of spatiotemporal variability in merged total water storage changes using multiple GRACE products and global hydrological models. Remote Sens. Environ. *192*, 198–216. https://doi.org/10.1016/j.rse.2017.02.011.
59. Richey, A.S., Thomas, B.F., Lo, M.H., Famiglietti, J.S., Swenson, S., and Rodell, M. (2015). Uncertainty in global groundwater storage estimates in a Total Groundwater Stress framework. Water Resour. Res. *51*, 5198–5216. https://doi.org/10.1002/2015WR017351.
60. Huang, Z., Pan, Y., Gong, H., Yeh, P.J.F., Li, X., Zhou, D., and Zhao, W. (2015). Subregional-scale groundwater depletion detected by GRACE for both shallow and deep aquifers in North China Plain. Geophys. Res. Lett. *42*, 1791–1799. https://doi.org/10.1002/2014GL062498.
61. Changming, L., Jingjie, Y., and Kendy, E. (2001). Groundwater exploitation and its impact on the environment in the North China Plain. Water Int. *26*, 265–272. https://doi.org/10.1080/02508060108686913.
62. Long, D., Yang, W., Scanlon, B.R., Zhao, J., Liu, D., Burek, P., Pan, Y., You, L., and Wada, Y. (2020). South-to-North Water Diversion stabilizing Beijing's groundwater levels. Nat. Commun. *11*, 3665. https://doi.org/10.1038/s41467-020-17428-6.
63. Zhang, C., Duan, Q., Yeh, J.-F., Pan, Y., Gong, H., Moradkhani, H., Gong, W., Lei, X., Liao, W., Xu, L., et al. (2021). Sub-regional groundwater storage recovery in North China Plain after the South-to-North water diversion project. J. Hydrol. (Amst.) *597*. https://doi.org/10.1016/j.jhydrol.2021.126156.
64. Zhao, Y., Zhu, Y., Lin, Z., Wang, J., He, G., Li, H., Li, L., Wang, H., Jiang, S., He, F., et al. (2017). Energy Reduction Effect of the South-To-North Water Diversion Project in China. Sci. Rep. *7*, 15956. https://doi.org/10.1038/s41598-017-16157-z.
65. Liu, X., Liu, W., Liu, L., Tang, Q., Liu, J., and Yang, H. (2021). Environmental flow requirements largely reshape global surface water scarcity assessment. Environ. Res. Lett. *16*, 104029. https://doi.org/10.1088/1748-9326/ac27cb.
66. Liu, J., Liu, Q., and Yang, H. (2016). Assessing water scarcity by simultaneously considering environmental flow requirements, water quantity, and water quality. Ecol. Indic. *60*, 434–441. https://doi.org/10.1016/j.ecolind.2015.07.019.
67. Sun, S., Zhou, X., Liu, H., Jiang, Y., Zhou, H., Zhang, C., and Fu, G. (2021). Unraveling the effect of inter-basin water transfer on reducing water scarcity and its inequality in China. Water Res. *194*, 116931. https://doi.org/10.1016/j.watres.2021.116931.
68. Cheng, Z., Zhao, Y., Song, T., Cheng, L., and Wang, W. (2023). White Elephant or Golden Goose? An Assessment of Middle Route of the South-to-North Water Diversion Project from the Perspective of Regional Water Use Efficiency. Water Resour. Manage. *37*, 819–834. https://doi.org/10.1007/s11269-022-03405-9.
69. Fan, L., Gai, L., Tong, Y., and Li, R. (2017). Urban water consumption and its influencing factors in China: Evidence from 286 cities. J. Clean. Prod. *166*, 124–133. https://doi.org/10.1016/j.jclepro.2017.08.044.
70. Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., et al. Complexity of Coupled Human and Natural Systems.
71. Pohlner, H. (2016). Institutional change and the political economy of water megaprojects: China's south-north water transfer. Global Environ. Change *38*, 205–216. https://doi.org/10.1016/j.gloenvcha.2016.03.015.
72. Kamp, U., Growley, B.J., Khattak, G.A., and Owen, L.A. (2008). GIS-based landslide susceptibility mapping for the 2005 Kashmir earthquake region. Geomorphology *101*, 631–642. https://doi.org/10.1016/j.geomorph.2008.03.003.
73. (2022). National Bureau of Statistics: consumer price index. http://www.stats.gov.cn/search/s?qt=%E6%B6%88%E8%B4%B9%E8%80%85%E7%89%A9%E4%BB%B7%E6%8C%87%E6%95%B0&siteCode=bm36000002&tab=all.
74. Changjiang Water Resources Commission of The Ministry of Water Resources (2001). The Plan of East Route of the South-north Water Transfer Project (China Water Power Press).

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Water consumption, domestic water consumption and water resources of each city	National Bureau of Statistics of China	http://data.stats.gov.cn/index.htm
The volume of transferred water of each city	Ministry of water resources of China	http://www.mwr.gov.cn/sj/tjgb/szygb/
The map of China	China's Resource and Environment Science and Data Centre	https://www.resdc.cn/data.aspx?DATAID=243
The eco-climate regions in China	China's Resource and Environment Science and Data Centre	https://www.resdc.cn/data.aspx?DATAID=125
Software and algorithms		
ArcGIS	ESRI	https://www.arcgis.com/index.html
R Studio	R Studio Team	https://www.r-project.org/
Origin 2022b	OriginLab	https://www.originlab.com/OriginProLearning.aspx
SPSS 22.0	IBM SPSS	https://www.ibm.com/cn-zh/spss
GeoDA	Luc Anselin, University of Chicago	https://geodacenter.github.io/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to the corresponding author (zhangxl@hku.hk).

Materials availability

This study did not generate new unique materials.

Data and code availability

Data: All data needed to evaluate the conclusions in the paper are present in the paper and/or the supplemental information. Additional data related to this paper can be requested from the authors.

Code: This paper does not report original code.

METHOD DETAILS

Water resources status evaluation

The indicators of water resources status were water stress, efficiency, and transfer. Water stress was defined as water resources development intensity (WDI), which refers to the degree of disturbance by human activities on the water system and related natural ecosystems. Water stress was measured by the proportion of water consumption to local water resources. Past work shows that the larger the WDI index, the greater the water stress.[31,57] Water efficiency was defined as the extent to which water resources contribute to urban economic growth and was measured by the proportion of water consumption to the local GDP and calculated by water consumption per GDP (WCG), which is widely used as an indicator to measure water efficiency.[68] The portion of the city using transferred water was measured by the RTW index, calculated by the ratio of water transferred is the proportion of the local water consumption used by non-local water, which reflects how much non-local water was used by urban development. High risk and cost are two features of transferred water[71,72]; thus, the less water transferred, the better. To effectively compare WCG index in different years, the GDP used in calculating WCG index was adjusted to 2019-based value using the consumer price index, which was obtained through China's National Bureau of Statistics.[73] The formulae used were.

Water stress:

$$WDI_i = \frac{W_i}{WR_i} \times 100 \quad \text{(Equation 1)}$$

Water efficiency:

$$WCG_i = \frac{W_i}{GDP_i} \quad \text{(Equation 2)}$$

Water transferred:

$$RTW_i = \frac{WT_i}{W_i} \times 100 \quad \text{(Equation 3)}$$

where WDI_i denoted the WDI index of the *i-th* sample city (%), a smaller value indicates a lower water stress. W_i is the water consumption of the *i-th* sample city (m^3), which includes surface water, groundwater and reuse water supply to domestic, production ,and ecological water consumption. WR_i is the water resources of the *i-th* sample city (m^3), which includes precipitation, surface water, groundwater, and transferred water. WCG_i is the water consumption per unit of GDP of the *i-th* sample city (m^3/kCNY), a smaller value reflects consuming less water to conduct economic growth and indicates higher water efficiency. GDP_i is the *i-th* sample city's gross regional product value in that year (kCNY), RTW_i is the *i-th* sample city's ratio of transferred water in that year (%), a smaller value indicates less transferred water was used in water consumption. And WT_i is the amount of water transferred to the *i-th* sample city in that year (m^3), which refers to the physical water transferred to the city.

Water resources management effects evaluation

By using the WCG index, we evaluated the economic growth conducted by water consumption. We further took GDP as the objective function, the amount of investment in fixed assets in urban water facilities, water consumption, and population were taken as capital, resources, and population input factors, respectively, to measure the efficiency of water resource utilization in the production of economic output. We have defined it as the water efficiency in the utilization process (WUE) in this study. The WUE index reflects the extent to which maximum economic growth is achieved with the minimum utilization of water resources.

DEA determines the relative effectiveness of Decision Making Units (DMUs) by keeping the DMU input or output unchanged, projecting DMUs onto the production frontier with the help of mathematical planning and statistics, and comparing the degree of deviation. One of the key characteristics of DEA is the ability to make an objective determination of the weightings between the evaluated inputs and outputs.

In the DEA model, suppose there are *n* DUMs, and each DMU_j has *m* items to input X_j ($x_{1j}, x_{2j},..., x_{mj}, x_{ij}$ >0) and *s* items to output Y_j ($y_{1j}, y_{2j},..., y_{sj}, y_{ij}$ >0). λ_j is the weight vector of the input and output of the DUM, and the efficiency value θ of each DMU_j satisfies:

$$E = \min \theta \quad \text{(Equation 4)}$$

$$\text{s.t.} \begin{cases} \sum_{j=1}^{k} X_j \boldsymbol{\lambda}_j \le \theta X_0 \\ \sum_{j=1}^{k} Y_j \boldsymbol{\lambda}_j \ge Y_0 \\ \boldsymbol{\lambda}_j \ge 0, j = 1, 2, \cdots, k \end{cases} \quad \text{(Equation 5)}$$

where the efficiency value θ is between 0 and 1. When θ = 1, DUM is DEA valid; when θ <1, it is DEA invalid, in which case the value of θ is large, indicating that the DUM is more efficient. In other words, a larger value of DEA indicates a higher WUE index. All the scenarios were defined as DMUs in DEA; thus, there are 193 DMUs in this study.

The water amount of investment in fixed assets in urban water facilities, water consumption, and population are taken as capital, resources, and population input factors, respectively, and the GDP of the municipal district is taken as the economic output factor.

The domestic water consumption per capita (WCP) reflecting awareness of water conservation and WCP index is given by

$$WCP_i = \frac{WD_i}{P_i} \quad \text{(Equation 6)}$$

where WCP_i denotes the per capita domestic water consumption of the *i-th* sample city (m^3/capita/year), a smaller value reflects people consuming less domestic water and indicates higher awareness of water conservation. WD_i is the domestic water consumption of the *i-th* sample city (m^3), And P_i is the *i-th* sample city's human population.

Theil index for water stress inequality (WST) and WST index can reflect the effect of the transferred water resources on mitigating their inequality.[32] Theil index provides a quantitative measure of the inequality of water stress levels at different temporal and geographic scales. A higher Theil index corresponds to greater inequality. We calculated Theil index to analyze water stress inequality quantitatively and its trend in the cities.

$$WST = \sum_{i=1}^{n} \left[ww_i \times \log\left(\frac{\mu}{WDI_i}\right) \right] \quad \text{(Equation 7)}$$

$$\mu = \sum_{i=1}^{n} [ww_i \times WDI_i] \quad \text{(Equation 8)}$$

$$ww_i = \frac{W_i}{\sum_{i=1}^{n} W_i} \quad \text{(Equation 9)}$$

where WST is the inequality of water scarcity, a higher value indicates a greater inequality. WDI_i is the water resources development intensity of the *i-th* sample city (%), W_i is the water consumption of the *i-th* sample city (m^3), and ww_i is the share of water consumption in 193 cities.

Finally, we defined an aggregated water resources management effects index (WRMEI) each year and WRMEI index is given by

$$WRMEI_j = \frac{\sum_i Q_i \times R_i}{D} \quad \text{(Equation 10)}$$

where Q_i is weight of *i-th* indicator, this study gave equal weights for each indicator and thus $Q_i = 1/3$, R_i is rank of *i-th* indicator of water resources management effects, and D denotes the total number of research years, $WRMEI_j$ denotes the *j-th* year's water resources management effects index, the $WRMEI_j$ index is between the [1/3, 1], and the change of $WRMEI_j$ index reflects the trend of effects generated by water resources management, the increase of $WRMEI_j$ index indicates that water resources management has a positive effect.

Methods of evaluating the impact of water transfer on GDP

Water transfer is importing non-local water from a basin with abundant water resources to those in shortage. This helps balance water quantities between basins and addresses water demands in water-deficient areas.[5] The available freshwater is transferred from one basin to another basin, and then, according to the planning of the government, decision-makers and policymakers allocate transferred water to different provinces and cities. Scholars evaluated the economic changed by water transfer projects in China from the perspective of the basin.[49] Based on this, this study developed an evaluation methodology to assess the impact of water transfer on GDP at the city-level.

The impact of water transfer on GDP was measured using two indices: total construction cost and the opportunity cost of the importing city (or opportunity benefit for water receiving city).

For water importing city j, the opportunity cost can be calculated as:

$$C_j = \frac{WT_{i,j}}{WCG_j} \quad \text{(Equation 11)}$$

where c_j denoted the economic opportunity cost of the *j-th* water importing city (kCNY), W_i is the water consumption of the *i-th* sample city (m^3). $WT_{i,j}$ is the amount of water transferred from the *j-th* city to the *i-th* city in that year (m^3), And WCG_j is the water consumption per unit of GDP of the *j-th* water importing city (m^3/kCNY).

For water receiving city i, the opportunity benefit can be calculated as:

$$B_i = \frac{WT_{i,j}}{WCG_i} \quad \text{(Equation 12)}$$

where c_j denoted the economic opportunity benefit of the *i-th* water reciving city (kCNY), WCG_i is the water consumption per unit of GDP of the i-*th* water reciving city (m^3/kCNY).

The opportunity for an increase in GDP can be calculated as:

$$\mathrm{p} = \frac{\sum B_i - \sum C_j}{GDP_{i,j}} \times 100 \quad \text{(Equation 13)}$$

where p denoted the percentage of increased opportunity in GDP (%), $GDP_{i,j}$ is the annual GDP of the provinces of the *i-th* and *j-th* city (kCNY).

Statistical analyses

To analyze the relationships among water stress, efficiency, transfer, and awareness of water conservation, correlation analysis was carried out to determine the correlation between the factors and how they affect each other.

Spatial analyses

ArcGIS (10.5) and GeoDa (1.18.0) were used to conduct spatial autocorrelation analysis for the 193 cities to identify local clusters and spatial outliers. To analyze whether a spatial aggregation regularity existed between water stress, water efficiency, the ratio of water transferred, and awareness of water conservation in a different city, 'hot spot' analysis was carried out by ArcGIS (10.5). In addition, to analyze the spatial aggregation regularity in the correlation between urbanization and water utilization, bivariate local Moran's I statistic by GeoDa (1.18.0) and spatial overlay analysis by ArcGIS (10.5) were carried out.

Study area

193 cities in mainland China were utilized (their spatial distribution and names are shown in Figure S1; Table S1, respectively) where accurate data were available. The cities had different population sizes, determined by urban population and include 15 of the country's 16 megacities. The size of cities from the data used include: 70%, 68%, and 65% of large, medium, and small cities in 2019.[46] Factors leading to changes in water demand are diverse, including socioeconomic development, climate change, and public policies and strategies. Therefore, based on the analysis of the current water situation and considering the prevailing climate at the location of the city, the cities were divided into five different eco-climate regions (See Table S2). At the same time, according to the "notice on adjusting the standard of city size classification",[46] the study cities are divided into five categories according to their population size. We used clusters to analyze the sample cities, which are classified into four categories according to GDP. We also used clusters to divide cities into four categories according to GDP per capita (See Table S2). This study fully reflects the relationship between urban water stress, water efficiency, and water transfer in the country. Since the conception of the South-to-North Water Transfer Project supply water in 2013, many cities have begun to use inter-basin water diversion sources,[67] with most of the transferred water intended for urban residential and industrial use.[47,49] To reflect the impact of water transferred on national urban water stress, we chose a 10-year timescale from 2011 to 2019 in this study, which both conclude the years with and without a large amount of water transferred to the city.

Data source

The data concerning water utilization and socioeconomic were collected from different databases, including the Water Resources Bulletin, the Statistical Yearbook of each city, and others. The map data were downloaded from China's Resource and Environment Science and Data Centre (https://www.resdc.cn/data.aspx?DATAID=125).