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Evaluating Losses from Water Scarcity and Benefits of Water Conservation Measures to Intercity Supply Chains in China

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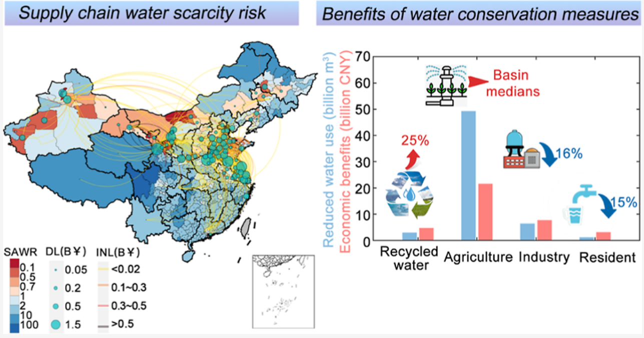

ABSTRACT: The severe water scarcity in China poses significant economic risks to its agriculture, energy, and manufacturing sectors, which can have a cascading effect through the supply chains. Current research has assessed water scarcity losses for global countries and Chinese provinces by using the water scarcity risk (WSR) method. However, this method involves subjective functions and parameter settings, and it fails to capture the adaptive behaviors of economies to water scarcity, compromising the reliability of quantified water scarcity loss. There is a pressing need for a new method to assess losses related to water scarcity. Here, we develop an agent-based complex network model to estimate the inter-regional and intersectoral impacts of water scarcity on both cities and basins. Subsequently, we evaluate the supply chain-wide economic benefits of four different water conservation measures as stipulated by the 14th Five-Year Plan for the Construction of a Water-Saving Society. These measures include increasing the utilization rate of recycled water in water-scarce cities, reducing the national water consumption per industrial value-added, and implementing agricultural and residential water conservation measures. Results show that direct losses constitute only 9% of the total losses from water scarcity. Approximately 37% of the losses can be attributed to interregional impacts. Among the water-scarce cities, Qingdao, Lanzhou, Jinan, and Zhengzhou pose a significant threat to China's supply chains. Agricultural water conservation yields the highest amount of water savings and economic benefits, while residential water conservation provides the highest economic benefit per unit of water saved. The results provide insights into managing water scarcity, promoting cross-regional cooperation, and mitigating economic impacts.

KEYWORDS: *water scarcity loss, water conservation measure, benefit evaluation, agent-based model, supply chain network*

■ INTRODUCTION

Water scarcity is a global issue affecting 2−4 billion people.[1,2] The water resource crisis was identified by the World Economic Forum in 2020 as the most significant societal risk on a global scale.[3] China accounts for 20% of the world's population and 7% of the world's freshwater resources, resulting in a per capita water resource possession equivalent to only one-fourth of the world average.[4] The disparity in the spatial distribution of water resources and the human population exacerbates the local water scarcity.[5] In addition to insufficient water quantity, pollution exacerbates a region's water scarcity by rendering water unsuitable for different uses and reducing freshwater availability.[6] The escalating severity of water scarcity may impact various sustainable development goals (SDGs), either through direct or indirect pathways.[7] Water scarcity poses significant risks to sectors such as energy, agriculture, and manufacturing[8] that rely heavily on water, and the impact can be transmitted through supply chains to other regions and sectors.[9] Quantifying economic losses from water scarcity can clarify the crucial role of water resources, promoting public awareness of water resource protection. Assisting decision-makers in formulating effective water resource management strategies to mitigate the adverse effects of water scarcity on economic growth.

In terms of water scarcity assessment, existing studies mainly focus on water quantity metrics using indicators such as per capita water resources;[10] the water stress index (WSI), defined as the ratio of water withdrawal or consumption to water availability;[11,12] the proportion of water supply from renewable freshwater resources;[13] and the water poverty index, which is the weighted average of water availability, access, capacity, use, and environment.[14] Subsequently, attention has been shifted to green−blue water footprint-based assessment, which measures

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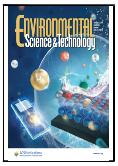

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the amount of water used in the production of goods and services consumed by humans. To assess water quality's impact on water scarcity, studies have introduced the concept of the gray water footprint.[15] This refers to the volume of water needed to dilute pollutants in wastewater to meet water quality standards,[16] encompassing indicators such as chemical oxygen demand (COD), ammonia nitrogen (NH^{+4}–N), and electrical conductivity (EC).[6] Ultimately, researchers introduced environmental flow requirements (EFR) to compose the quantity-quality-EFR (QQE) water scarcity assessment approach.[17] In this study, only one water quantity metric was employed to assess cities' water scarcity. In future research, these water quantity and quality metrics can be integrated with the developed adaptive-agent-based modeling framework.

The damage of water scarcity includes adverse effects on human health[18] and ecosystems.[19] These are often quantified using the end-point indicators of life cycle assessment (LCA) methods,[20] which assess the overall water resource utilization of products or services throughout their entire lifecycle. Damage is also reflected in the availability of resources (especially food)[21] and social conflict.[22] Moreover, water scarcity leads to economic losses. Early studies used water resource shadow pricing models to evaluate the economic losses from water scarcity,[23] but they could not account for supply chain cascading effects. Researchers then turned to input–output models to investigate the economic repercussions of water scarcity on economic sectors where water is not a critical part of their production process through sectoral interlinkages and supply chains.[24] However, these studies ignored cross-regional impacts, where local water scarcity can influence distant regions through trade systems.[25,26] To address this issue, studies quantified the local water scarcity risk (LWSR) for each region-sector by utilizing the WSI and sectoral water intensity. The impacts of LWSR transmitted to downstream sectors through reduced input supplies are evaluated using a global multiregional input–output (MRIO) model.[27] However, this approach has limitations, like subjective function and parameter settings, making it better for relative sector rankings than quantifying absolute monetary losses. The MRIO method assumes fixed and linear production factor ratios and prices, failing to capture adaptive behaviors.[28] The above method framework has been used to assess water scarcity losses for global countries,[29,30] China,[31] and Chinese provinces.[6,32,33] However, these assessments have overlooked the diverse water scarcity levels among different cities within the same province[5] and the complexity of supply chain transmission between cities. Here, we introduce an indicator that reflects the urban production water scarcity degree by considering human water consumption, environmental flow requirements, and total water resources. We develop an agent-based complex network model to assess the impact of water scarcity on the supply chain at the prefecture-level city scale. The direct losses are determined through optimization using the linear programming module in the model, while indirect losses are simulated through our model, capturing various adaptive behaviors of economies when facing water scarcity.

As water scarcity is exacerbated by climate change and social-economic development,[34] there's a growing need for adaptive measures.[35] However, existing literature has concentrated on analyzing the cost-effectiveness of individual water conservation measures in specific regions, such as recycled water utilization,[36] agricultural water conservation,[37] and industrial water conservation.[38] The economic benefits considered have typically included only direct benefits such as saved water resources and environmental benefits, without the benefits of alleviating water scarcity in other sectors through the implementation of water conservation measures as well as the indirect benefits that propagate through the supply chain network. Building upon the aforementioned framework for water scarcity loss assessment, we evaluate the water savings and overall economic benefits of four distinct water conservation measures. This aids in determining the investment intensity and implementation sequence of these water-saving measures.

In this study, we construct a city-level water satellite account for 313 Chinese prefecture-level cities (regions) using 2010–2019 water use and total water resource data. We evaluate the water scarcity in each city and calculate the sectoral production of water-scarce cities under water constraints. We design a water resource-driven multiagent economic system model by incorporating water resources as the constraints for production, which can simulate various adaptive behaviors of the economy in the face of water scarcity. We evaluate the total national loss caused by water scarcity at the city and basin scales in China and estimate the reduction in economic losses due to implementing water conservation measures.

METHODS AND DATA

In this study, we first assess the water scarcity of each city and then input the calculated water scarcity indicators into our agent-based complex network model to calculate the direct and indirect economic losses of each water-scarce city (or basin), and the method is shown in Figure S1. Finally, we evaluate the benefits of each water conservation measure based on the above complex systems model.

City-Level Water Scarcity Assessment. We investigate average annual agricultural, thermal, and nuclear power, other industrial excluding thermal and nuclear power, and domestic water use in each prefecture-level city from 2010 to 2019, while eco-environmental compensation water use is relatively small and is not considered in our study. Given the unavailability of detailed water use data at the sector level, the different types of water use are allocated to the corresponding sectors in the MRIO according to the value of water provided by the *Production and Distribution of Tap Water* sector to other sectors in the 2017 MRIO[39] (see Supporting Information Method 1). To ensure sustainable water resource management and prioritize the preservation of natural ecosystems and their normal functioning, a proportion of renewable water resources is reserved for river, lake, wetland, and other aquatic ecosystem use, following the EFR.[40] Based on the criteria for classifying water scarcity levels,[1] we have set the ratios of EFR to the total water resources at 60, 70, and 80%. The remaining water is allocated for human use and consumption. Therefore, the quantitative indicator for water scarcity in this study, the sectoral available water ratio (SAWR), is as follows

$$\mathrm{WC}_{r,s} = \mathrm{WU}_{r,s} \times \mathrm{WCR}_{r,s} \tag{1}$$

$$\mathrm{SAWR}_r = \frac{\mathrm{WA}_r \times (1 - \mathrm{EFRR}) - \sum_{s=43}^{44} \mathrm{WC}_{r,s}}{\sum_{s=1}^{42} \mathrm{WC}_{r,s}} \tag{2}$$

$$\mathrm{WI}_{r,s} = \frac{\mathrm{WC}_{r,s}}{\bar{X}_{r,s}} \tag{3}$$

where $\mathrm{WCR}_{r,s}$ represents the water consumption ratio (ratio of water consumption to water usage) of sector s in region r; $\mathrm{WC}_{r,s}$ is the water consumption of sector s in region r; WA_r is the water available in area r; EFRR is the environmental flow requirement ratio (EFRR) (taking 60, 70, and 80%, respectively); $\overline{X}_{r,s}$ is the production capacity at the pre-event level of sector s in region r; and $\mathrm{WI}_{r,s}$ is the water consumption intensity of sector s in region r.

Supply Chain Loss due to Water Scarcity. We develop an agent-based complex network model to assess the impact of water scarcity on supply chains by integrating and extending previous models,[41−43] which are mostly used to evaluate the supply chain losses of natural disasters.[42,44−48] The specific mathematical descriptions and formulas are comprehensively detailed in Supporting Information Method 2. The model parameters are listed in Table S2. The network structure of the model is derived from the MRIO, where the region-sector is the production agent, the final consumption of each region is the consumption agent, and the transportation agent is the transportation chain connecting all agents, reflecting the time required for transporting products. They are defined to interact in a complex way in the virtual world.[49] Production agents can produce products and send products and orders to other agents connected in the supply network; if external shocks (such as a shortage of raw materials or production capacity loss caused by natural disasters) occur, they can show certain adaptive behaviors, such as replenishing inventory, adjusting the order share of upstream suppliers, adjusting production technology, etc. Consumption agents can use the products and send out the orders. A transportation agent can load, transport, and unload products. Our agent-based model is deterministic rather than probabilistic. It does not involve profit maximization, cost minimization, or price mechanisms. Instead, all agents follow established behavior patterns. These agents mainly interact in two ways: transporting products between regions through transportation chains and exchanging information, including sharing orders and production status updates.

If a city faces a water scarcity under the set EFRR (SAWR < 1), it should reduce production to reduce water usage until the production water usage equals the amount allowed for production. The production aims to maximize the total output[8,29] of a water-scarce city while taking into account the constraints of water availability, total orders, production capacity, and raw material supply

$$\max \mathrm{TO}_r = \sum_{s=1}^{42} X_{r,s}^{a} \tag{4}$$

$$\sum_{s=1}^{42} (X_{r,s}^{a} \times \mathrm{WI}_{r,s}) \le \left(\sum_{s=1}^{42} \mathrm{WC}_{r,s}\right) \times \mathrm{SWAR}_r \tag{5}$$

$$0 \le X_{r,s}^{a} \le \min\{O^{\mathrm{tot}}, X^{\mathrm{cap}}, \min\{X^{s'}\}, \min\{X^{r',s'}\}\} \tag{6}$$

where TO_r represents the total output in the region r; ${X_{r,s}}^{a}$ is the actual production in the region r; O^{tot} denotes the total order; O^{cap} is the production capacity; and $X^{s'}$ and $X^{r',s'}$ are the production constraints due to the inventory of intermediate product s' ($X^{r',s'}$ is the case for specific product s' such as a particular type of machine component); the other behaviors of the agents are summarized in Supporting Information Method 2.

Due to the absence of detailed daily data, our model simulates on a weekly scale, assuming uniform production, water availability, and water usage each week at the steady state. We begin by using the prefecture-level city MRIO to assign values to the Chinese economy in our model. The model then automatically initializes the world and its agents and computes other necessary variables. The resulting water consumption intensity matrix and the city's SAWR are input to our model, and agents are connected and act in the given order. The model repeats this process for a total of 52 time steps and will output every time step of production agents' variables including value-added $[\mathrm{VA}_{r,s}(t)]$, intermediate products, etc. We define the value-added decrease (compared with the steady-state value) of all production agents as the impacts of water scarcity. For production agents directly impacted by water scarcity, their losses can be categorized into two parts: (1) reduction of value-added in water-scarce areas and sectors caused by production cuts and (2) additional reduction in value-added caused by the spread of production reduction through the supply chain. We designate the occurrence of a water shortage in the first step of the simulation. Therefore, the decrease in the value-added of production agents in the first step is a direct loss. The first category represents a direct loss ($\mathrm{DL}_{r,s}$), while the second category represents an indirect loss ($\mathrm{TL}_{r,s}$).

$$\mathrm{DL}_{r,s} = \overline{\mathrm{VA}}_{r,s} - \mathrm{VA}_{r,s}^{t=1} \tag{7}$$

$$\mathrm{TL}_{r,s} = \overline{\mathrm{VA}}_{r,s} \times T - \sum_{t=1}^{T} \mathrm{VA}_{r,s}(t) \tag{8}$$

$$\mathrm{IL}_{r,s} = \mathrm{TL}_{r,s} - \mathrm{DL}_{r,s} \tag{9}$$

For each EFRR level (60, 70, and 80%), we initially conducted simulations to assess the supply chain impacts of water scarcity in individual cities. For the basin-level water scarcity loss assessment, we have inducing water scarcity in all deficient cities within the basin. The detailed methodology is in Supporting Information Method 3.

Benefits of the Water Conservation Measures. The National Development and Reform Commission, the Ministry of Water Resources, and other government departments released a plan for China to become a "water-saving society" by the end of the 14th Five-Year Plan period. The aim is to increase the utilization rate of recycled water in water-scarce cities at the prefecture level and above nationwide to greater than 25% and reduce the national water consumption per 10,000 CNY of industrial value-added by 16% from 2020 levels by 2025. Furthermore, the plan includes various water conservation measures for the agriculture and residential sectors. Considering the fairness, feasibility, and improvement effectiveness, we aim to reduce the water consumption per 10,000 CNY of *Agriculture* sector value-added in each city to the median level of its corresponding basin, while also implementing a 15% reduction in per capita residential water consumption across all cities.[50] Assuming that the water usage demand remains constant, water usage and corresponding water consumption from the natural environment in the respective sectors will decrease after implementing water conservation measures, resulting in a new water use satellite account calculated as follows

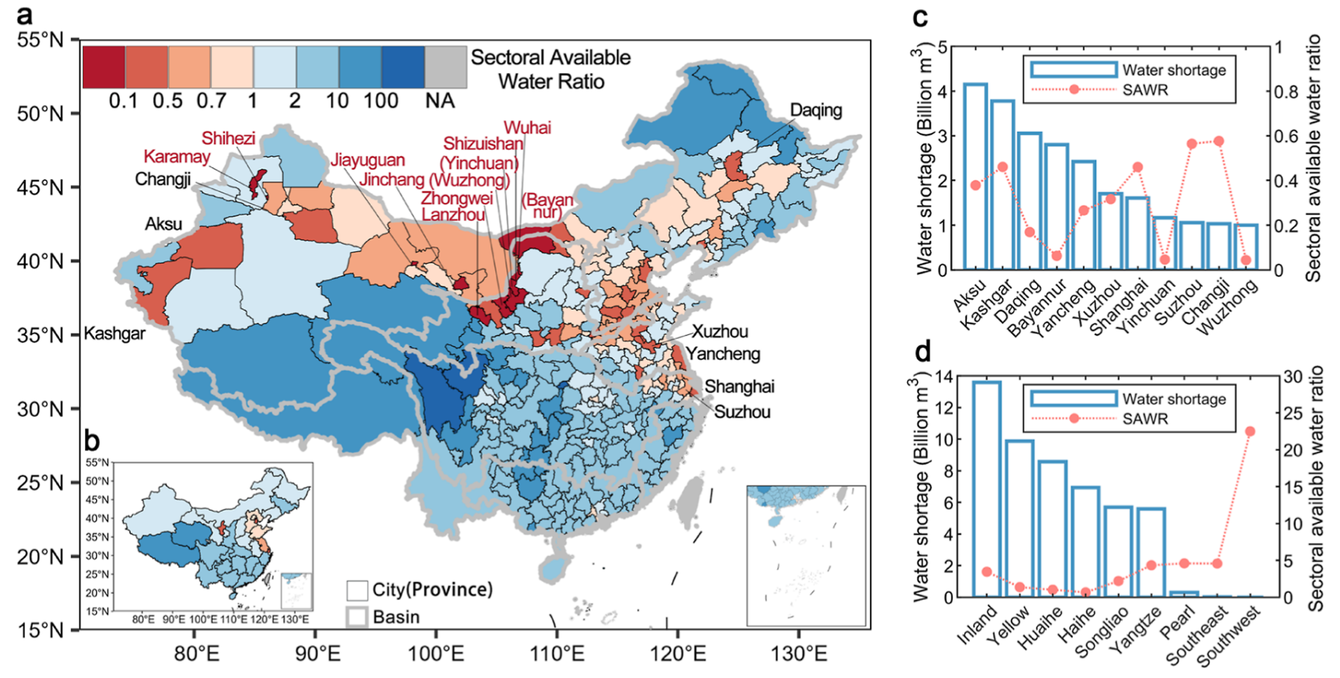

Figure 1. SAWR in 313 regions (a) and 31 provinces (b) when the EFRR is 60%. Cities with an SWAR less than 0.1 are marked in red, and cities with water shortage greater than 1 billion cubic meters are marked in black; cities in parentheses have both situations. Water shortage and SAWR for the top 11 cities of water shortage (c) and nine basins (d). The water shortage is the sum of water consumption (by sectors and residents) and EFR minus the total water resources, and if the result is greater than 0, it indicates a water shortage.

$$\mathrm{WU}^{\mathrm{Rw}}_{r,s} = \mathrm{WU}_{r,s} \times \frac{(1+(1-\mathrm{WCR}_{r,s})\beta_r)}{(1+(1-\mathrm{WCR}_{r,s})\beta_r')} \qquad (10)$$

where β_r is the recycled water utilization rate of water-scarce city r in 2020, which is equal to the recycled water usage divided by total sewage treatment; β_r' is the recycled water utilization rate in 2025 (25%); $\mathrm{WU}_{r,s}$ is the water use before; and $\mathrm{WU}_{r,s}{}^{\mathrm{Rw}}$ is the water use after.

$$\mathrm{WU}^{\mathrm{Agr}}_{r,1} = \bar{X}_{r,1} \times \mathrm{WI}_{r,1} \qquad (11)$$

where $\bar{X}_{r,1}$ is the output of the first (*Agricultural*) sector in region r; $\mathrm{WI}_{r,1}$ is the water use intensity in region r after agricultural water conservation implementation, as described in Supporting Information Method 4.

$$\mathrm{WU}^{\mathrm{Ind}}_{r,2-27} = \mathrm{WU}_{r,2-27} \times (1 - 16\%) \qquad (12)$$

$$\mathrm{WU}^{\mathrm{Red}}_{r,43-44} = \mathrm{WU}_{r,43-44} \times (1 - 15\%) \qquad (13)$$

$$\mathrm{WU}^{\mathrm{All}}_{r,s} = \mathrm{WU}_{r,s} - (4\mathrm{WU}_{r,s} - \mathrm{WU}^{\mathrm{Rw}}_{r,s} - \mathrm{WU}^{\mathrm{Agr}}_{r,s} - \mathrm{WU}^{\mathrm{Ind}}_{r,s} - \mathrm{WU}^{\mathrm{Red}}_{r,s}) \qquad (14)$$

where $\mathrm{WU}_{r,2-27}{}^{\mathrm{Ind}}$, $\mathrm{WU}_{r,43-44}{}^{\mathrm{Red}}$, and $\mathrm{WU}_{r,s}{}^{\mathrm{All}}$ represent the new water satellite accounts after the implementation of industrial water conservation, residential water conservation, and the above four measures together, respectively.

After implementing each water conservation measure, we obtained a new water use satellite account. The water use reduction in each city is shown in formula 15. According to the methodology in (1–9) above, we calculate the economic losses caused by water scarcity that still exist after implementing the measure and compare them with the benchmark scenario without implementing the measure. The reduction in economic losses is the economic benefits. We evaluate the economic benefits of each measure separately for each city under the scenario with an EFRR of 60%, as shown in the formula 16.

$$\mathrm{RWU}^{\mathrm{wsm}}_{r} = \sum_{s=1}^{44} (\mathrm{WU}_{r,s} - \mathrm{WU}^{\mathrm{wsm}}_{r,s}) \qquad (15)$$

$$\mathrm{REL}^{\mathrm{wsm}}_{r} = \sum_{r=1}^{313} \sum_{s=1}^{42} (\mathrm{TL}_{r,s} - \mathrm{TL}^{\mathrm{wsm}}_{r,s}) \qquad (16)$$

Data Sources. We use the latest Chinese city-level MRIO table[51] for the year 2017, compiled by China Emissions Accounting and Datasets (CEADs). The table is divided into 313 regions (including 309 prefecture-level administrative units and 4 municipalities directly under the Central Government), each of which contains 42 sectors. The data set has been widely used to calculate carbon emissions[52] and virtual water[53] in China.

Data on the water usage of agricultural, industrial [direct current thermal (nuclear) power], and domestic as well as water availability for 356 prefecture-level cities (except for Hong Kong, Macao, and Taiwan) in 31 provinces from 2010 to 2019 are obtained from city and provincial Water Resources Bulletins. Data are averaged annually to exclude the effects of fluctuations in the short term. The MRIO table used in this paper only contains 313 regions, of which Tibet, Yunnan, Qinghai, and Hainan are entire provinces with no subdivision of cities. We match the 356 cities with the 313 regions in MRIO, and the corresponding data are aggregated to obtain water use and water availability data for the 313 regions. Data on water transfers in 2017 are taken from the Water Resources Bulletins of the corresponding recipient cities. The national water consumption ratios for 44 sectors are taken from ref 39, and it is assumed that all regions have the same water consumption ratio in the same sector. Data on renewable water

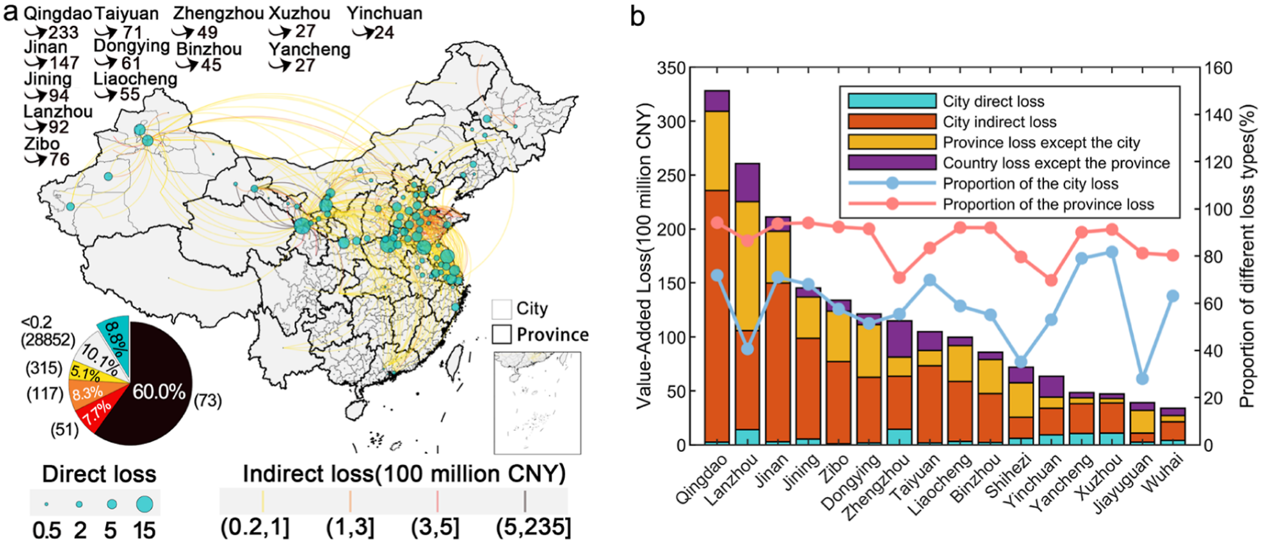

Figure 2. Economic impact of water scarcity in cities under an EFRR of 60%. (a) The size of the blue circles represents direct economic losses caused by reduced output due to water scarcity in each affected city, while the line color represents the indirect economic losses of other cities incurred by the water scarcity. The top left corner represents the indirect economic impact of a water-scarce city on itself. The lower left corner pie chart represents the percentage of each type of economic loss. The numbers in brackets represent the number of indirect economic loss flows in the corresponding range. (b) Economic impact distribution of the 16 cities with the highest impacts.

usage and total sewage treatment for 2020 can be obtained from the China Urban Construction Statistical Yearbook. The resolution, time period, and source of water-related data are listed in Table S3.

RESULTS

City-Level Water Scarcity. When EFRR is 60%, 95 cities exhibit water scarcity (SAWR < 1), as shown in Figure 1a. These cities are primarily in the inland river basins; the Songliao, Haihe, and Yellow River basins; and the Yangtze River Delta regions. There are 11 cities with an SAWR less than 0.1, mainly located along the upstream of the Yellow River due to their limited total water resources. When we use the difference between water consumption and total water resources to indicate the absolute water shortage (Figure 1c,d), we find that the cities with the highest water shortage are mainly located in the Yangtze River Delta and Xinjiang due to the high (industrial or agricultural) water demand. Summing up the water shortages of each city in the basin, we found that the inland river basin has the highest water shortage. SAWR values for each city under an EFRR of 70 and 80% are shown in Figure S2.

When calculating SAWR for entire provinces (Figure 1b), only 7 provinces show water scarcity. Notably, provinces with numerous water-scarce cities like Xinjiang, Gansu, Inner Mongolia, and Henan do not register as water-scarce at the provincial level. Similarly, when assessing entire basins, only the Haihe River basin has an SAWR < 1. This highlights the necessity of focusing our study at the city level rather than on the provincial, basin, or even national level.

Supply Chain Loss Assessment for Water Scarcity. Table S4 summarizes various estimates of water scarcity losses based on different definitions and research scopes. The first estimate assesses actual losses due to water supply interruptions, totaling around 10 billion CNY.[54] The second and third assessments evaluate the potential risks related to water scarcity. The third assessment assumes year-round water scarcity, resulting in estimates exceeding 1 trillion CNY.[6,29] We consider the second assessment, with a range of 200−300 billion CNY,[55] more reasonable from an environmental perspective and use it as a benchmark to calibrate our results. We set the duration of water scarcity in water-scarce cities to 1 week using empirical data, adjusting the inventory size in our agent-based complex network model (Figure S3). Furthermore, we calculate the economic benefits of the South−North Water Transfer Central Project based on our estimated water scarcity losses, demonstrating the practical value of our assessments (Figure S4).

Figure 2a illustrates losses due to water scarcity in cities with an EFRR of 60%. Blue circle sizes represent direct losses in water-scarce cities. Cities like Zhengzhou, Lanzhou, Xuzhou, and Yancheng incur around 1 billion CNY each, while Yinchuan, Xianyang, Karamay, and Shihezi face 0.6−1 billion CNY in direct losses. These 95 water-scarce cities account for 22.27 billion CNY in direct losses, comprising 8.8% of the total losses. On the other hand, water scarcity impacts are not confined to local areas but rather are transmitted throughout the country via supply chains. The total indirect economic loss is 230.45 billion CNY, 59.6% of which is the indirect impact of the water-scarce city on itself. Water scarcity has intercity impacts that occur at different scales and transfer between cities in the Heilongjiang, Shandong, Shanxi, Gansu, and Xinjiang provinces. For instance, losses can originate from Harbin in Heilongjiang, Taiyuan in Shanxi, and Lanzhou in Gansu and affect cities located within the same province. However, they can also transfer across provinces, such as between cities in the Yangtze River Delta and those in the Beijing−Tianjin−Hebei region.

Figure 2b displays the losses from 16 critical water-scarce cities, causing over 3 billion CNY in national losses, comprising 75.6% of the total losses. Each city's direct losses contribute 1−20% of the total. Shandong cities have less than 5% direct losses, while Yinchuan, Zhengzhou, and Wuhai range from 10 to 20%. Conversely, Xuzhou and Yancheng exceed 20%, primarily due to the sector (agricultural vs industrial) affected by water scarcity. Shorter supply chains in agriculture lead to

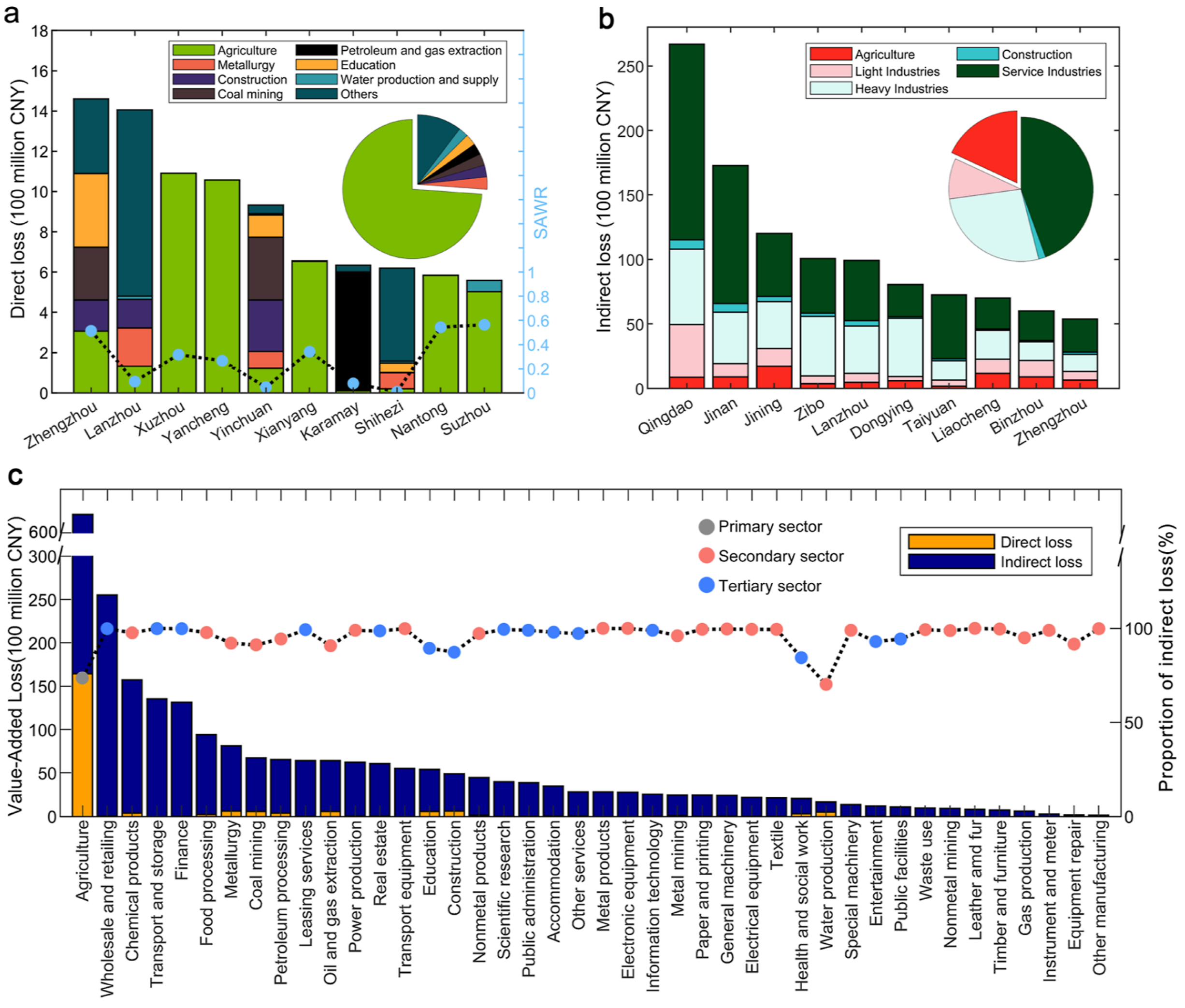

Figure 3. (a) Distribution of direct economic losses of the top 10 cities in terms of direct economic losses. Pie chart showing the distribution of total direct economic losses of 95 water-scarce cities. (b) Distribution of indirect economic losses of the top 10 cities. Pie chart showing the distribution of indirect economic losses of all cities. (c) Aggregated direct and indirect economic losses by sector.

higher direct loss ratios. Within these cities, 50−70% of losses occur locally. Lanzhou, Shihezi, and Jiayuguan exhibit lower proportions, suggesting that fewer downstream industries are affected by water scarcity-induced production reductions. However, Xuzhou and Yancheng have higher proportions. 5−20% of total losses affect other provinces, with Yinchuan, Zhengzhou, and Shihezi contributing relatively more. This underscores their pivotal roles in the national supply chain.

Cities in the same basin can simultaneously experience water scarcity. Therefore, we simulate simultaneous water scarcity in basin cities to assess its impact (Figure S5). The Yellow, Huai, Haihe, and inland river basins face water resource inadequacies, leading to direct economic losses of around 16.1 billion CNY, comprising 72.7% of all basin losses. Indirect impacts are primarily between the Yellow, Huai, and Hai River basins and the Haihe River basin's effect on the Yangtze River basin.

Figure 3a shows that the total direct losses of the 95 water-deficient cities are mostly concentrated in the *Agriculture* sector (74%), with the remaining losses mainly occurring in six other sectors (averaging 2.5%). These sectors have a higher water demand per unit of output and thus will reduce production first. The SAWR of the top ten cities in terms of direct losses is all less than 0.6, indicating that the direct losses of water-scarce cities depend on their SAWR and GDP. Generally speaking, the smaller the SAWR, the more sectors will experience direct economic losses. For example, in Lanzhou, Yinchuan, Karamay, and Shihezi (with an SAWR less than 0.1), the direct losses occurred in 10−30 sectors. Yinchuan and Shihezi have significant direct losses in several industrial sectors, such as the *Mining and Washing of Coal* and Manufacture of Chemical Products sectors, resulting in significant impacts on other provinces. The direct losses of Zhengzhou and Suzhou occurred in sectors other than the *Agriculture* sector, while the remaining five cities all experienced direct losses only in the *Agriculture* sector. This is because the *Agriculture* sector accounts for only about 25% of the total water use of the 42 sectors in Zhengzhou and Suzhou (compared to around 70% in the other five cities). Overall, this indicates that the direct losses are influenced by a combination of the SAWR, GDP, and proportion of water use in the *Agriculture* sector.

Figure 3b shows the top ten cities with the highest indirect losses, mostly aligning with those causing the greatest total losses in Figure 2b. However, some Shandong cities rank higher due to 70% of their water scarcity-induced losses occurring locally, with their industrial chains primarily within the province, resulting in more significant losses for other cities

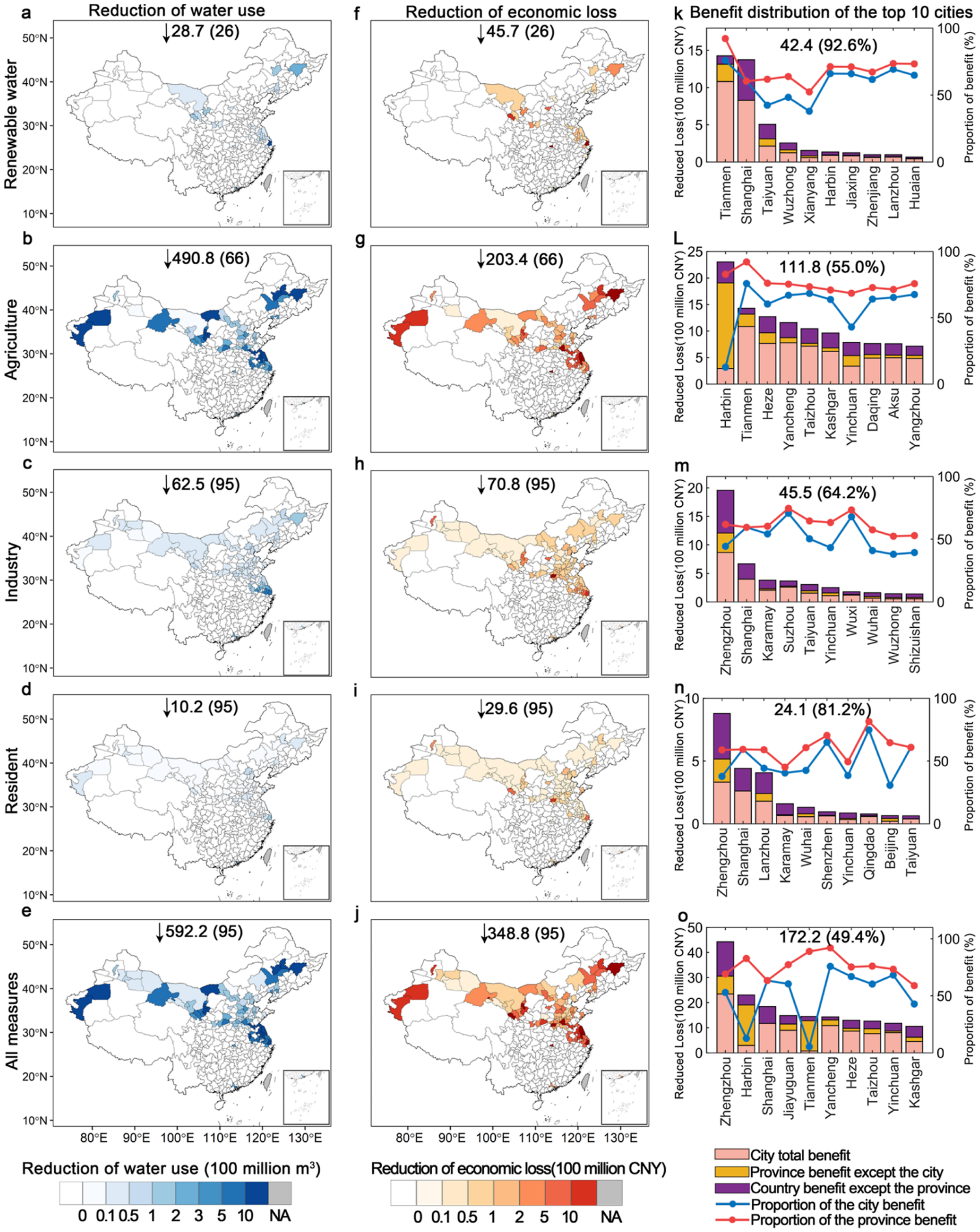

Figure 4. Amount of water saved in (a−e) and economic losses reduced in (f−j) by cities implementing various water conservation measures. The colors in (f−j) represent the reduction in total national losses due to the implementation of water conservation measures. The numbers represent the sum of reductions in water use or economic losses (number of cities). (k−o) is the distribution of economic benefits for the top 10 cities in terms of total economic benefits; the numbers represent the sum (share) of benefits for the cities.

in the province during water scarcity. Among the top ten cities with indirect losses, only Lanzhou and Zhengzhou ranked in the top ten for direct losses. This suggests that direct loss magnitude is not the sole determinant of indirect losses. The types of affected industries, industrial chain localization, and GDP play crucial roles in the indirect loss determination. We categorized each city's indirect losses into five sector groups: service industries (44.4%), light and heavy industries (35.9%), and the *Agriculture* sector (18.1%). In the top ten cities, the proportion of losses in the *Agriculture* sector is less than 18%. This could be because water scarcity has already severely

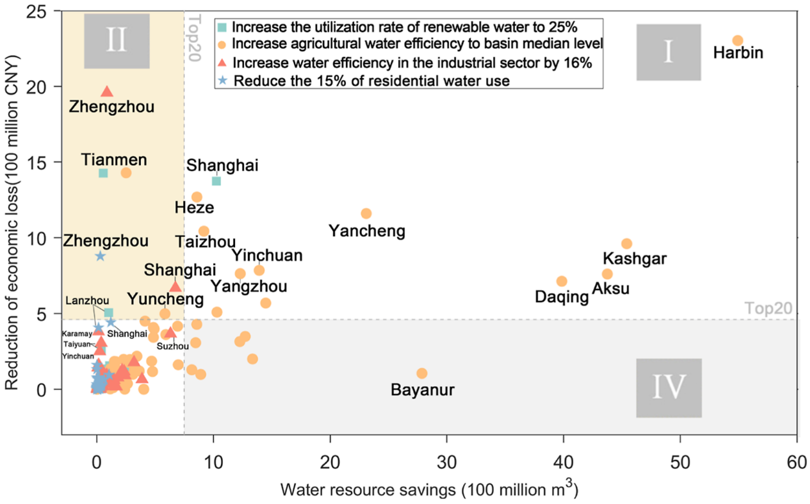

Figure 5. Water-saving volume and economic losses avoided (i.e., economic benefits) by implementing water conservation measures in water-scarce cities.

impacted the *Agriculture* sector in these cities, resulting in relatively fewer subsequent indirect effects.

Figure 3c summarizes the direct and indirect sectoral losses for all cities. We find that indirect losses in the *Agriculture* and *Production and Distribution of Tap Water* sectors account for about 70%, while the *Construction* and *Health care and social work* sectors account for about 85%. The remaining sectors have indirect losses that account for more than 90%. The impact of water scarcity can be transmitted through the supply chain to sectors that are not experiencing water scarcity, highlighting the importance of collaboration between sectors. The *Agriculture* sector has the highest total indirect loss of 45.67 billion CNY as it includes different subsectors such as farming, forestry, animal husbandry, and fishery, which are interconnected through the supply chain. The highest sector's direct losses lead to the largest indirect losses. In the service industries, the combined indirect losses of the *Wholesale and Retail Trades, Transport, Storage and Information Technology Services*, and *Finance* sectors account for 22.6% of the total indirect losses as these service sectors have many upstream sectors and are heavily impacted by supply chain disruptions. For the manufacturing sectors, except for the *Manufacture of Chemical Products* sector, the other sectors have relatively equal indirect losses. We observe that the total economic losses of the secondary sectors are generally lower, while the tertiary sectors tend to experience relatively higher losses. This is attributed to the higher value-added by each tertiary sector, leading to proportionally higher losses when the same shock propagates through the supply chain.

The previous section illustrates how water scarcity affects supply chains at a 60% EFRR, but EFRR should ideally be 60—80%.[1] Therefore, we also study the losses by city/basin at 70 and 80% EFRRs (Table S5).

Benefits of Implementing Water Conservation Measures. From the "14th Five-Year Plan for the Construction of a Water-Saving Society", we identified four water conservation measures as described in the Methods section above. In Figure S6, the recycled water utilization rates required for the first water conservation measure in all 313 regions in 2020 are displayed. Figure 4 depicts water usage reduction and economic loss mitigation in water-scarce cities postimplementation of diverse conservation measures. Our findings reveal that enhancing the water efficiency in agriculture yields the most significant water savings and economic benefits. On average, agriculture consumes 62.3% of the annual water use (Figure S7), making it a prime target for water-saving improvements. High economic benefits stem from substantial water savings, which can alleviate output declines in crucial industrial sectors with high output values and pivotal supply chain positions. Raising the recycled water utilization rate to 25% has a limited impact in cities where it is already at or near this threshold. In addition, cities with low residential water usage yield lower savings and total economic benefits. However, residential water conservation delivers the highest economic benefit per unit of water saved at 2.9 CNY/m^3 (Figure S8). This is especially significant in cities facing severe water scarcity, where freeing up additional water for high-value industrial sectors results in substantial economic gains, even reaching 50 CNY/m^3 in some cases. Our findings also reveal that approximately 55% of the economic benefits resulting from the implementation of water conservation measures in water-scarce cities occur within the city, while 70% occur within the province. The higher proportion of this ratio in agricultural water conservation compared to industrial and residential conservation can be attributed to the regional confinement of downstream supply chains associated with the *Agricultural* sector within the city or province, in contrast to industrial sectors. A detailed explanation of the distribution of benefits from water conservation measures can be found Supporting Information Result.

Figure 5 presents the water-saving volume and benefits resulting from water conservation measures in water-scarce cities. We selected the top 20 cities in terms of water-saving volume and economic benefits and categorized the 282 cities implementing water conservation measures into four categories. Category II contains cities that achieve significant economic benefits while reducing water usage, including economically developed cities like Shanghai and Zhengzhou and cities with severe water scarcity like Lanzhou. Category IV contains cities achieving limited economic benefits despite significant water reductions. These include cities that have implemented agricultural water-use efficiency measures. Category I encompasses cities with both high economic benefits and significant water reductions. We assess the economic benefits per unit of conserved water for each city implementing water-saving measures (Figure S9). We find that the majority of water conservation measures with per-unit benefits of >20 (CNY/m^3) are residential water conservation measures, and these cities generally had limited water resources.

DISCUSSION

This study presents a method for evaluating the impacts of water scarcity on intercity supply chains and the benefits of water conservation measures in terms of reducing economic loss and water withdrawal. By using a multiagent complex network model coupled with water resource and use data, the study reveals a complex landscape of interwoven factors such as water scarcity, direct and indirect impacts on supply chains, and various water conservation measures. To confront such complexity, effective water management strategies depend on understanding the spatial and temporal heterogeneity of the interactions of these factors.

We assessed the economic losses caused by water scarcity in cities and basins individually using previous estimates[55] of the total economic loss due to water scarcity in China as macroconstraints for our agent-based model. At the city level, the results indicate that only 9% of the observed losses stem directly from production reductions caused by water scarcity, with the *Agricultural* sector being the primary contributor due to its highest water consumption intensity. However, the remaining 91% of losses are interregional and intertemporal effects through the propagation of supply chains. The direct losses from water scarcity are particularly severe in cities such as Zhengzhou, Lanzhou, Xuzhou, Yancheng, and Yinchuan. It is urgently necessary to enhance the water efficiency through practical policies and incentive measures coupled with the construction of essential water facilities such as reservoirs. Particularly, the *Agricultural* sector is of vital importance because it supplies food and raw materials to diverse industries.[56] Under scenarios of water scarcity, a reduction of water consumption in agriculture may lead to food shortages, higher food prices, and other negative impacts on the economy and farmers' livelihoods.[57] For the *Agricultural* sector in these cities, adopting dry-farming,[58] drip irrigation,[59] and other technologies is crucial to reduce agricultural water use and associated losses. Cities experiencing significant indirect losses are primarily concentrated in Shandong Province, attributed to the region's developed industrial sector, wherein both upstream and downstream elements of the supply chain are centralized within the province. Therefore, it is imperative to establish an intercity water resource allocation mechanism and the diversity and resilience of upstream suppliers to mitigate the local supply chain's vulnerability[60,61] to the transmission of water scarcity-related losses.

The impact of water scarcity extends beyond water-scarce cities, with 37% of the losses being attributed to interregional effects. This indicates that nationwide water resource management across regions and sectors is crucial. Improving the construction (such as the water network construction in the "Ji Zi Bay" of the Yellow River) and management (the South-to-North Water Diversion Project's Eastern Route) of water diversion projects can alleviate water scarcity in receiving areas.[62−64] Additionally, a nationwide or regional emergency response mechanism, particularly between Gansu, Shaanxi, and the Yangtze River Delta city cluster, for efficient water scarcity mitigation should be established.[65] Among the cities facing water scarcity, Qingdao, Lanzhou, Jinan, and Zhengzhou present a substantial threat to China's supply chains, which are primarily determined by the ratio of available water for production to actual water usage and the GDP of these cities. Priority should be given to addressing water scarcity in these cities through implementing water quotas and promoting innovative water-saving technologies. Additionally, efforts should be focused on advancing water supply projects to collectively reduce water scarcity levels and mitigate nationwide losses.

Due to regional variations in hydrogeological conditions, climatic factors, ecosystem sensitivity, and other natural elements, the ratio of EFR to total water resources exhibits temporal−spatial differences.[66] Therefore, it should not be entirely uniform. Lacking detailed city-level data, this study applies the same ratio of EFR for all cities, assessing water scarcity and associated losses under EFRR values of 60, 70, and 80%. The uniform EFRR may introduce uncertainty into the results. Actual measurements of EFR in Chinese provinces indicate that calculating the national EFR total with an EFRR of 60% yields an approximately 10% higher total.[67] The uniform EFRR underestimates the EFR for certain northern cities, leading to an underestimation of both their water scarcity levels and the losses incurred from water scarcity. Therefore, future research should conduct actual measurements of EFR in different regions.[17]

Based on the assessment of water scarcity and its impact on supply chains, we can evaluate the water savings and economic benefits of four water conservation measures implemented in cities. In general, improving the efficiency of agricultural water use saves the most water resources and brings about the greatest economic benefits. We propose transitioning to the Agricultural Water Efficiency Leader Program to bolster agricultural water conservation measures. Concurrently, mechanisms such as water rights trading markets have been established, encouraging economically rewarding practices for agricultural efficiency. Given that enhancing the agricultural water efficiency can free up enough water for other sectors, we suggest that water-intensive industries allocate funds for promoting agricultural water conservation measures. Residential water conservation measures provide the highest unit water-saving economic benefits, necessitating increased investment in promoting and popularizing residential water conservation technologies and appliances. We investigate which water conservation measures were implemented in which cities could generate greater per-unit economic benefits, both within the city and nationwide, such as industrial and residential water conservation measures in Zhengzhou, an increased utilization rate of renewable water in Tianmen and Shanghai, and the implementation of agricultural water conservation measures in cities like Tianmen, Heze, and Taiyuan. Funds and resources should be prioritized for allocation to these cities to implement their respective water conservation measures. Our results show that approximately 45% of the economic benefits of implementing water conservation measures occur outside the city. This suggests that financially affluent regions should provide funding to less developed, water-deficient cities for the development of water-saving technologies.

This study presents a framework for assessing supply chain-wide losses caused by water scarcity and the effectiveness of various water conservation measures. However, the numerical results may be uncertain due to the assumptions made in the absence of relevant data. For instance, in constructing the city-level water use satellite account, we assume that the water prices are the same for all industrial or service sectors in a city. Other methods[68,69] can be used to construct the water use satellite account to severely robust the conclusions. Additionally, this study also assumes the same water consumption rate in the same sector of different cities as well as the same recycled water use rate in each sector. Future research should address other limitations of this study. Also, the assessment of water scarcity should incorporate the water quality dimension to implement a three-dimensional evaluation including water quantity and quality and environmental flows.[70] This study has not yet considered all water diversion projects, including the South-to-North Water Diversion Project, and water intake from the Yellow River in certain cities. Future research analyzing these aspects will yield further insights into optimizing water resource allocation and conservation measures.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c07491.

> Methods; methodological flow of this study; SAWR values for cities with 70% and 80% EFRRs; calibration of model parameters; validation the usability of the assessments; economic impact of water scarcity in basins; recycled water utilization rates; proportion of different types of water use and reduction in water use; total water saving and economic benefits; economic benefits per unit water saved; correspondence between the MRIO sectors and the types of water use; model parameters; data on water resources; external estimates of water scarcity losses; and losses under different EFRRs (PDF)

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Notes

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