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Reframing water demand management: a new co-governance framework coupling supply-side and demand-side solutions toward sustainability

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Abstract Water demand management adopts economic and non-economic measures to reduce human water use. However, it is argued in this study that water use changes may cause idle water supply facilities and revenue losses, thereby challenging the sustainability of water supply systems in the context of climate change. A co-governance framework was established to inspire practical strategies of sustaining water supply systems by re-evaluating the long-term impacts of water demand changes. This framework adopts a broader view of water demand management by integrating the political, financial, and consumptive needs of the government, the market, and the users in the form of a collaborative strategy coupling both supply-side and demand-side solutions. The proposed framework was applied to the analysis of the sustainability of China's South-to-North Water Diversion Project. It is found that the South-to-North Water Diversion Project is not a simple water supply infrastructure but rather a synthesis of supply-side and demand-side water management solutions. Actively releasing water for ecological and cultural purposes is suggested in this study to maintain the socioecological benefits of the project in the context of human water use decline. The economic cost of the water supply could be recovered by ongoing revenues that include not only the water fees charged to users but also the benefits gained from cooperative investment in broader water-related businesses by both the state-owned water-transfer company and local governments in water-receiving areas. The proposed framework and strategies are valuable for other water utilities around the world, especially those challenged by reduced water demand caused by climate change, high water prices, and economic depression.

1. Introduction

In recent decades, management reforms have been implemented worldwide for sustainable environmental governance in the context of increasing global concerns about environmental degradation (Zhang and Wen, 2008; Voulvoulis et al., 2017; Nesshover et al., 2017). However, existing efforts have been challenged by global environmental changes, especially intensifying climate change (Glaeser, 2022; Sharifi and Khavarian-Garmsir, 2020; Armstrong et al., 2022). These changes have brought unparalleled upheaval to global environmental sustainability over the past century (Leal et al., 2022; Martin-Arias et al., 2020; Peng et al., 2023).

Water plays a central role in various system transitions needed for climate-resilient development (FALKENMARK, 1997; Trenberth and Asrar, 2014). Four key stages of the shift in water demand over time have been put forward according to observations on global water use transitions: the exploratory stage, the expansion stage, the maturity/contraction stage, and the sustainable stage (Loch et al., 2020). In the early stage, the water use of a society increases rapidly as the population grows. This period has been referred to as the exploratory stage, during which extensive infrastructure is constructed to increase water supplies, leading to the next phase of expansion (Koutsoyiannis, 2011; Matrosov et al., 2015). In the expansion stage, the society's water use continues to increase, but with a slowing growth rate caused by the increasing economic and environmental costs of new water storage construction in the context of limited water resources and ecological degradation (Johnston, 2013). As the peak water supply is reached at this stage, water demand may flatten or decrease in the following mature or contraction stage due to demand management (Dawadi and Ahmad, 2013; Mohapatra and Mitchell, 2009; Al-Juaidi, 2020). Ideally, the total water demand will further reduce to a lower level in the sustainable stage, allowing sufficient water flow to be diverted from human society to ecosystems for continuous ecological restoration. However, as uncertainty associated with the impacts of climate change still exists in achieving long-term sustainability, water demand transitions to future phases could follow different potential paths, including increasing, flat, or decreasing demand depending on the water governance solutions adopted to adapt to the changing environment.

Existing methods for water demand management can help to identify shifts in human water demand. Generally, two classes of instruments, namely economic and non-economic measures, are adopted (Harou et al., 2009; Britton et al., 2013). Economic measures, including various water price regimes, such as tiered pricing structures (Smith, 2022; Sahin et al., 2018), block tariffs (Ruijs et al., 2008), peak/ladder pricing systems (Molinos-Senante, 2014; Ben Zaied and Binet, 2015), subsidies for water-saving facilities, and the water market, represent a least-cost strategy to increase water use efficiency (Sahin et al., 2018). Non-economic instruments include the utilization of unconventional water resources and persuasive or mandatory water savings. The primary objective of these measures is to reduce human water demand (Sowers et al., 2011; Cui et al., 2018; Shahraki et al., 2019; Zhang et al., 2017a). The reduction can be transient, such as short-term regulations during a drought period (Wang et al., 2020), or it can be persistent, as exemplified by the gradual and sustained reduction in water use observed in developed nations (Hart, 2016; Wheeler et al., 2017). For example, as shown in Figure 1, there has been a significant decrease in water use in the state of Victoria, Australia and in the United States since the 1970s and 1990s, respectively.

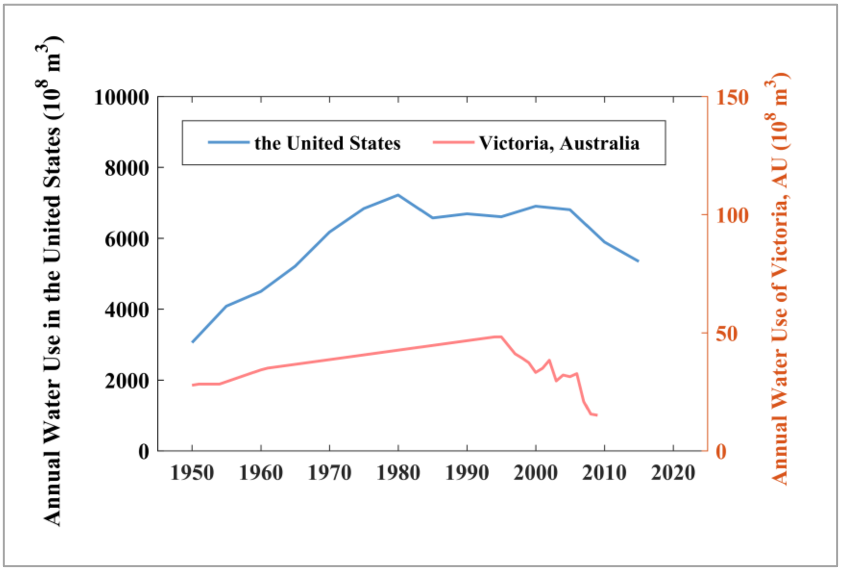

Figure 1 Annual water use in the United States and in Victoria, Australia

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However, there is not a clear understanding of whether this decline in water demand will continue under climate change and what its long-term impact will be. The overreliance on water demand-side solutions such as water-saving technologies or water markets may have possible negative impacts on both existing water supply systems and users. First, the marginal cost of water-saving will increase significantly and the long-term maintenance of water-saving facilities may cause a continuous economic burden to users with the widespread construction of water-saving facilities (Dawadi and Ahmad, 2013; De Loë et al., 2001). Second, pricing or water market solutions may have nonlinear outcomes that prioritize some users over others and fail institutional equity tests (Bakker et al., 2008; Jorgensen et al., 2009). For example, in dry seasons, farmers may abandon farming and sell their permanent water rights due to insufficient water supplies and high water prices to buy water from the market, resulting in the loss of the dairy industry in Victoria, Australia (Ding and Kinnucan, 2011) and a "Swiss cheese" impact on existing regional irrigation infrastructure (Gross and Dumaresq, 2014). In some cases, long-term declines in water use have occurred due to population reduction, the exit of farmers, and deindustrialization rather than water demand management measures (Wheeler, 2022). These reductions and exits have resulted in nonlinear outcomes of demand-side solutions that ignore the complex processes of irreversible and mutational outcomes arising from tipping points in the co-evolutional social–ecological system (Guo et al., 2007; Brandt and Merico, 2013), posing an ongoing challenge for sustainable water resource management(Liu et al., 2013; Pohlner, 2016).

It is impossible to rely solely on demand-side measures while neglecting supply-side considerations when dealing with sustainability issues. Water supply infrastructures provide the foundation for delivering stable and reliable water to both society and ecosystems. Ensuring healthy water supply systems is indispensable when the total water demand is decreasing toward a sustainable level but with possible reversals due to climate change. Given the above factors, a co-governance framework coupling supply-side and demand-side management was established in this study by casting light on the multifarious demand of water users and suppliers, with the aim of informing practical strategies that would enable the pathway of water governance to move toward sustainability in the context of a changing environment. The proposed framework was applied to China's South-to-North Water Diversion Project (SNWDP) by analyzing its benefits and challenges. Furthermore, a set of strategies including water price reform, active environmental water management, and broader revenue streams were provided to improve the sustainability of the project, which was stressed by the decreasing water demand in the water-receiving areas.

This study provides innovative insights on the interaction between supply-side and demand-side solutions within the case project, in particular: (1) establishing a new co-governance framework to sustain the water supply system in the case of decreased water demand under environmental change; (2) advancing the understanding of the impacts of climate change and decreased human water demand on reducing the revenues of water utilities; (3) for the first time, recommending a "win-win" strategy that could inspire further research on the cooperation between the central and local governments in China to cover the economic costs of the SNWDP to continuously supply ecological water to northern China.

2. Material and methods

2.1 Methods

A co-governance framework was established to increase the sustainability of water resource systems through understanding the emerging supply-side dilemma caused by water demand changes in the context of environmental change. Two underlying principles are justified when applying the framework in the analysis of water system sustainability, including (1) understanding the diversity, variability, and resilience of water demand and (2) recognizing the relationship between supply-side and demand-side management.

First, there are diverse forms of societal demand in water resource development, including not only the consumptive demand of water users but also the ecological water demand and the revenue requirements of water utilities. Moreover, non-linear processes exist in society's water demand change, as human water use could change drastically when reaching the tipping point arising from population migration and economic upgrades. In addition, the cross-seasonal resilience of ecological water use allows for ecosystem restoration during the dry season through releasing water to the ecosystem in the wet season.

Second, the demand-side and supply-side solutions are not separated in an advanced water governance system. It would be narrow-minded to define a water diversion project as solely a supply-side solution because the construction of water diversion projects could be accompanied by managing the water demand of water-receiving areas if the project is considered from a broader perspective incorporating national or regional water-saving initiatives. Many cases provide evidence for this perspective, including the water transfer from rural areas in the Murray-Darling basin, Australia to the Melbourne area, where community water use restrictions and the Target 155 initiative were adopted at the same time during the Millennium drought (Low et al., 2015). Target 155 encourages individuals to limit their water use in order to reach a daily average of 155 liters per person, per day (Lindsay et al., 2017).

Based on the above justifications, five key elements are proposed in the framework, including the following: (1) the national or regional institutional arrangements for better water governance in which the supply-side and demand-side management measures are embedded; (2) the diverse needs of stakeholders, including the water demand of the society and ecosystems, as well as the requirements for the sustainable development of water utilities; (3) the nonlinearity of variations in water demand arising from climate and socioeconomic changes; (4) active environmental water management; and (5) strategies for maintaining the revenues of water supply enterprises to cover the costs of long-term ecological water replenishment in the case of reduced human water demand. These elements are shown in Figure 2.

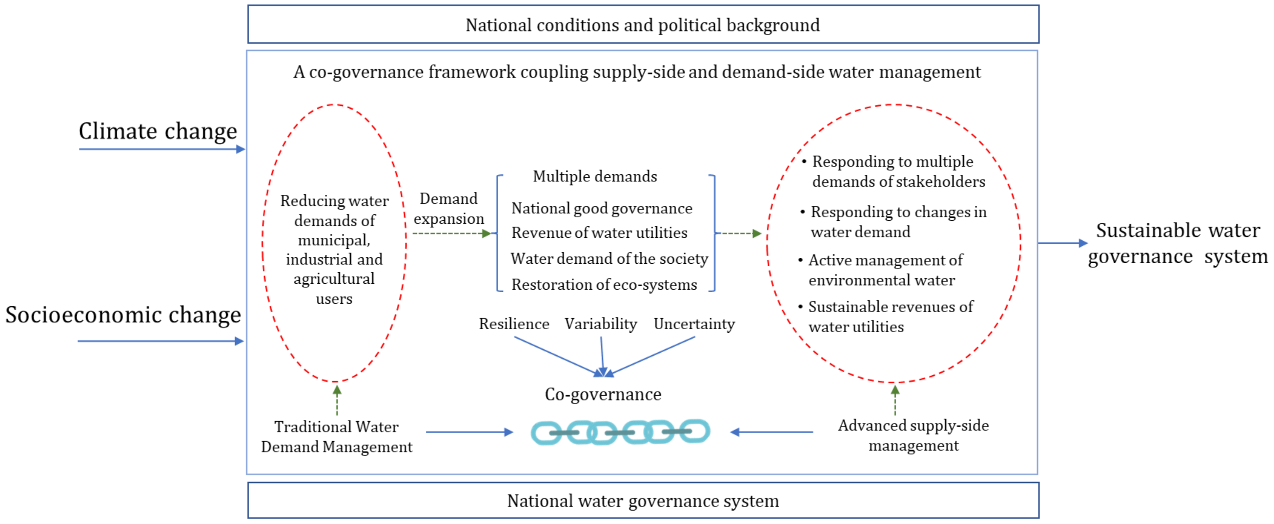

Figure 2 Co-governance framework coupling supply-side and demand-side solutions toward sustainability

2.2 Case Study

The SNWDP was approved by the State Council of China in 2002 after decades of efforts on debate, planning, design, and assessment beginning in the 1980s. The goal of the project was to transfer water from the Yangtze River Basin, which has a water surplus, to water-scarce northern China through three diversion routes: the East, Middle, and West routes. Construction of the East and Middle routes began in 2003 and 2005, respectively, and the routes were put into operation in 2013 and 2014, respectively. Since then, the East and Middle routes of the project have diverted a cumulative total of 60 billion cubic meters of water. The West route is still under debate due to its complex ecological impacts on the Tibet Plateau. The location of the East and Middle routes is shown in Figure 3.

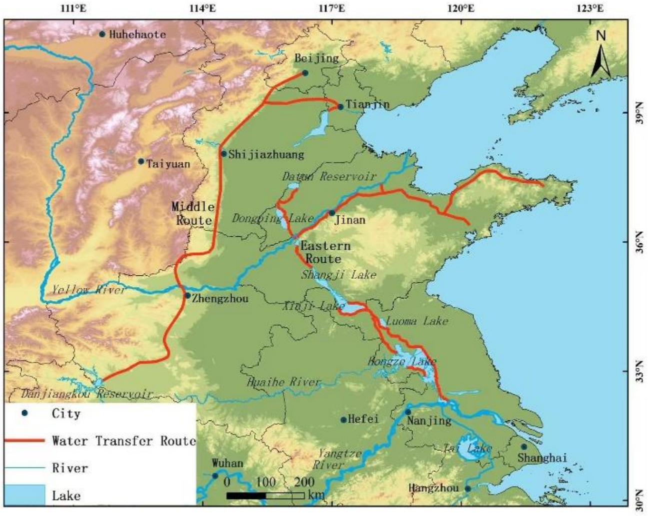

Figure 3 East and Middle routes of the South-to-North Water Diversion Project (SNWDP)

Note: DEM data is from SRTM digital elevation data, 2018 at https://bigdata.cgiar.org/srtm-90m-digital-elevation-database/

Although the SNWDP is already in operation, its necessity, benefits, and ecosystem impacts are topics of ongoing debate among researchers. The major arguments are shown in Table 1, including the debates on whether the project should be built and how it can operate sustainably in the future. These questions have not been adequately answered due to insufficient data on the project and the incomplete understanding of China's overall water governance system. Given the above factors, the benefit and the cost recovery of the SNWDP were re-analyzed in this study using the proposed co-governance framework in a wider perspective of sustainable water demand management.

Table 1 Arguments on the South-to-North Water Diversion Project (SNWDP)

Theme	Attitude	Perspectives	References
Benefits	Positive	The SNWDP has promoted economic growth and social development in northern China through increasing the water supply.	(Zhang et al., 2017b); (Li et al., 2022); (Hu et al., 2013)
	Negative	The water demand in northern China will increase due to the economic growth resulting from the augmented water supply.	(Zhao et al., 2015);

Theme	Attitude	Perspectives	References
			(Barnett, J., Rogers, S., Webber, 2015); (Li et al., 2019)
Impacts on ecosystems	Positive	The project has improved the ecological health of northern China through replenishing water to groundwater funnels in the water-receiving area.	(Zhang and Li, 2014); (Long et al., 2020)
	Negative	The reduction of water availability in the water-donating areas will lead to the loss of aquatic habitats and the intensification of salt tide intrusion in the Yangtze River estuary. Soil salinization caused by over-irrigation may occur in the water-receiving area.	(Tang et al., 2014) (Zhang, 2009) (Schmidt et al., 2020); (Webber et al., 2015); (Chen et al., 2013)
Cost recovery	Positive	Although the economy in northern China may continue to grow without the project, if driven by the overexploitation of water resources, this growth will cause further ecological degradation. The ecological benefits of the SNWDP should be included in recovering its expenses.	(Liu, 1998); (Zhou et al., 2012) (Berkoff, 2003)
	Negative	The energy consumption of pumping water to the north via the East route is huge and will reduce the economic efficiency of the project.	(Miao et al., 2018); (Sheng et al., 2020); (Fang et al., 2015)

3. Result

3.1 Re-evaluating the relationship between supply-side and demand-side management

It is believed that the evolution of human water demand follows several stages, as shown in Figure 4(a) (Loch et al., 2020). The water demand increases rapidly at the early stage, resulting in the expanding extraction of water resources. Following this stage, water supply augmentation through engineering measures is deemed unsustainable because of the increasing economic and ecological costs of extracting more water from rivers and aquifers. In this case, demand-side management is adopted to increase water use efficiency and eventually to reduce water demand or flatten the growth of water use. Based on this understanding, the SNWDP is simply justified as a supply-side measure in some studies, arguing that this "hard" engineering method of increasing the water supply is unable to efficiently address the issues of water scarcity in northern China.

In the present study, it is argued that the SNWDP is not a simple water supply infrastructure but a synthesis of supply-side and demand-side solutions if it is assessed in the broader context of national water governance. As a national initiative on water demand management, China's Water Law legalized water conservation as an essential justification in the water governance of China in 2002. Specific water conservation targets across the country were then proposed in a policy termed “the strictest water resource management,” which was issued by the Chinese central government in

2012. The 2030 targets include restraining the national water use to within 700 billion cubic meters, reducing the water consumption for every 10,000 yuan of industrial value added to below 40 cubic meters, and increasing the irrigation water use efficiency coefficient to above 0.6 (Wu et al., 2021). These targets were further assigned to different regions within China to assess the performance of their measures. These demand-side solutions at the national level provided a compulsory rule for the operation of the SNWDP, which required water-saving actions in the water-receiving area. In addition, the overall plan for the SNWDP launched in 2002 proposed a principle of "water-saving first," which prioritized water-saving before water transfer (Ministry of Water Resources, 2002). This principle was also legally confirmed by the "Water supply and management regulations for South-North water transfer project" in 2014 (State Council, 2014). Affected by the above measures, the total water demand in China has not increased and has even decreased slightly since 2014, when the SNWDP began supplying water to northern China, as shown in Figure 4(b). In addition, the active supply of ecological water in China increased significantly after the implementation of the project. These outcomes demonstrate that the SNWDP is not a traditional engineering method to increase water supply but rather an integrated governance system that includes both supply-side and demand-side solutions with the aim of increasing the ecological water supply driven by China's national initiatives on water saving and ecological restoration.

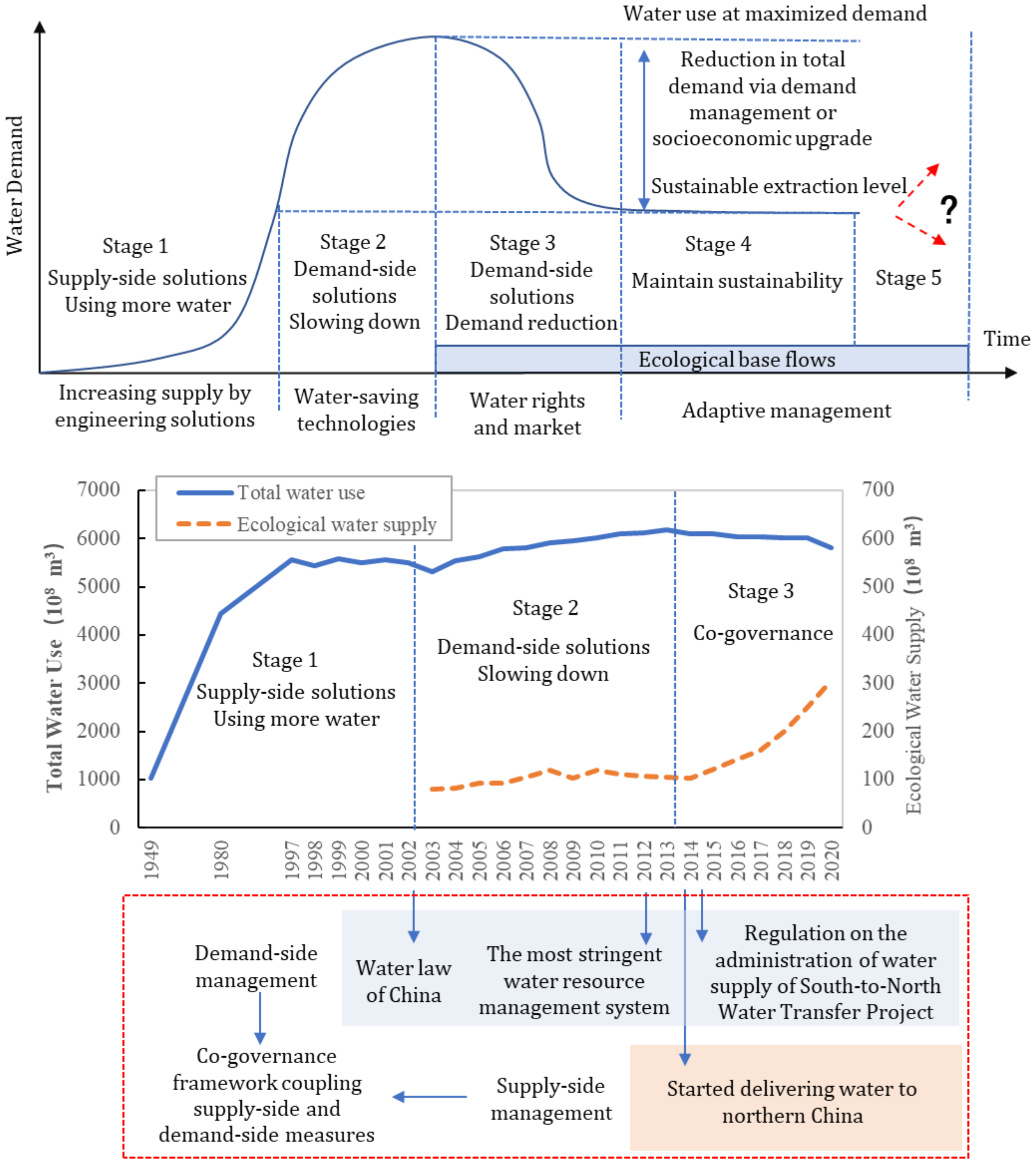

Figure 4 Co-governance of the water demand and supply of the South-to-North Water Diversion Project (SNWDP)

3.2 Re-evaluating the ecological benefits of a long-distance water diversion project

Improving environmental flows through reducing human water use is difficult throughout the world (Mercer et al., 2007). For example, although the buyback of water entitlements from consumptive to environmental use in the Murray-Darling River Basin, Australia is widely seen as successful and effective, the water entitlement recovery for environmental purposes has experienced and still faces difficulties, as the reallocation introduced environmental water rights holders, who are often in conflict with existing rights owners (irrigators) (Tisdell, 2010). Moreover, the buyback has not effectively reduced the inelastic water demand of consumptive users, unless high costs are paid for compensation, which impedes the long-term recovery of environmental flows. This is the major reason why the significant reduction of irrigation water proposed in the Basin Plan of the Murray-Darling River has met strong opposition from communities (Gale et al., 2014).

Unlike the above case, the co-governance system of China's SNWDP allocated the ecological water entitlement of the water-receiving area before the water transfer. The ecosystem is not a new emerging entitlement holder but an initial water user that has been identified since the planning stage of the project. For example, the water diversion route was adopted through prioritizing the pathway that passed areas with ecological water deficits. In addition, the “Regulations on the Supply and Use of Water for the South-to-North Water Diversion Project” stipulate that the major goal of the project is to restore the ecosystems of water-receiving areas through active environmental watering. This is the top priority of the project, which guides the entire process of project planning, construction, and operation.

As a result, the downward trend of the groundwater level in major parts of the water-receiving area has been significantly reversed since the SNWDP began operation in 2014, as shown in Figure 5(a). In addition, the water transferred from the Yangtze River directly provides environmental flows to rivers and lakes, thus increasing the water storage of northern lakes, including the Miyun Reservoir and Dongping Lake, as shown in Figure 5(b) and Figure 5(c). The Miyun Reservoir and Dongping lake provide major storage for the water from the East and Middle routes, respectively. The increased water storage in these reservoirs and lakes is actively used to augment the ecological water supplies for the local areas. The growth of the ecological water supply in the water-receiving area is shown in Figure 6, leading to the recovery of environmental flows in many formerly dry rivers.

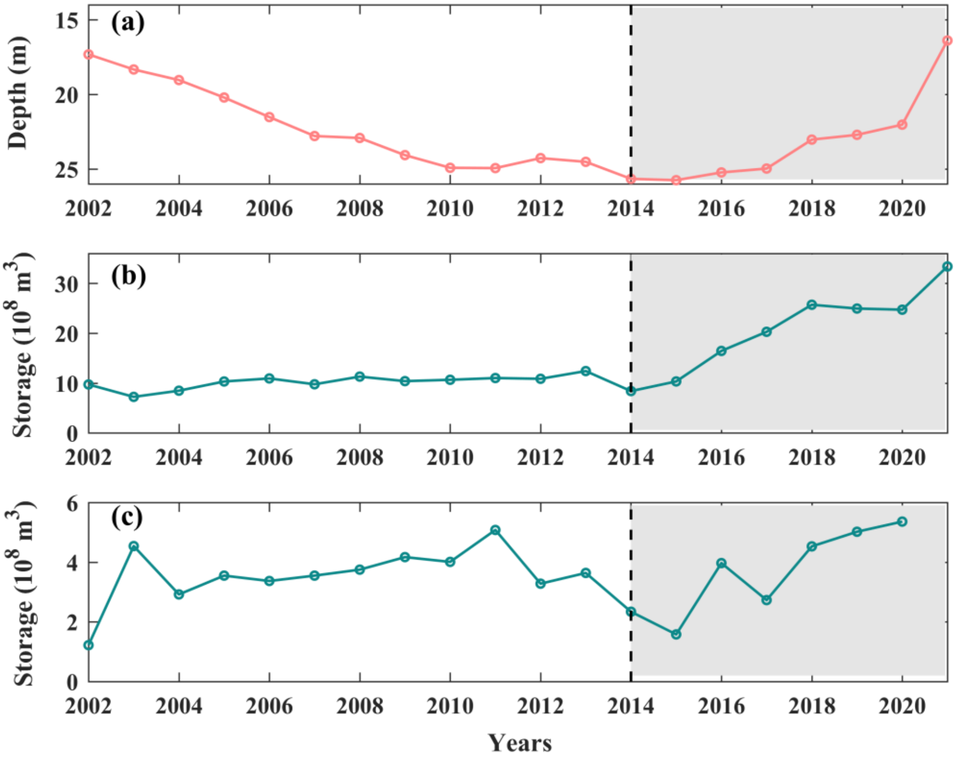

Figure 5 Impact of the South-to-North Water Diversion Project (SNWDP) on ecosystems in the water-receiving area

In addition, the SNWDP has made the entire route of the Beijing–Hangzhou Grand Canal navigable through directly delivering water to the canal since 2020. This has extended beyond environmental flow recovery by providing water reallocation for cultural purposes. China's Grand Canal, the longest artificial waterway in the world, was initialized in Spring and Autumn Period (770–476 BC) and completed in the Yuan Dynasty (1271 to 1368) by finally connecting the capital, Beijing, to Hangzhou city in the south. The total length of the Beijing–Hangzhou Grand Canal is 1710 km, and the canal is not only a valuable part of China's historical heritage but is also listed as a World Heritage Site by the UNESCO. Historically, the main function of the Beijing–Hangzhou Grand Canal was to ship the abundant grain from rainy southern China to the dry north to support population growth. However, due to siltation and drought, the northern section of the canal has been unnavigable since the Qing Dynasty (1644–1912). Since 2020, over 100 years since the northern section became unnavigable, ships can once more sail from Hangzhou to Beijing using the water released from the SNWDP. This has strong significance for cultural restoration in China as one of China's most famous pieces of historical heritage is once again in use. Water reallocation for cultural purposes is also admitted by other nations, including the recognition of cultural water demand in expanding the market water rights in Australia (Moggridge and Thompson, 2021).

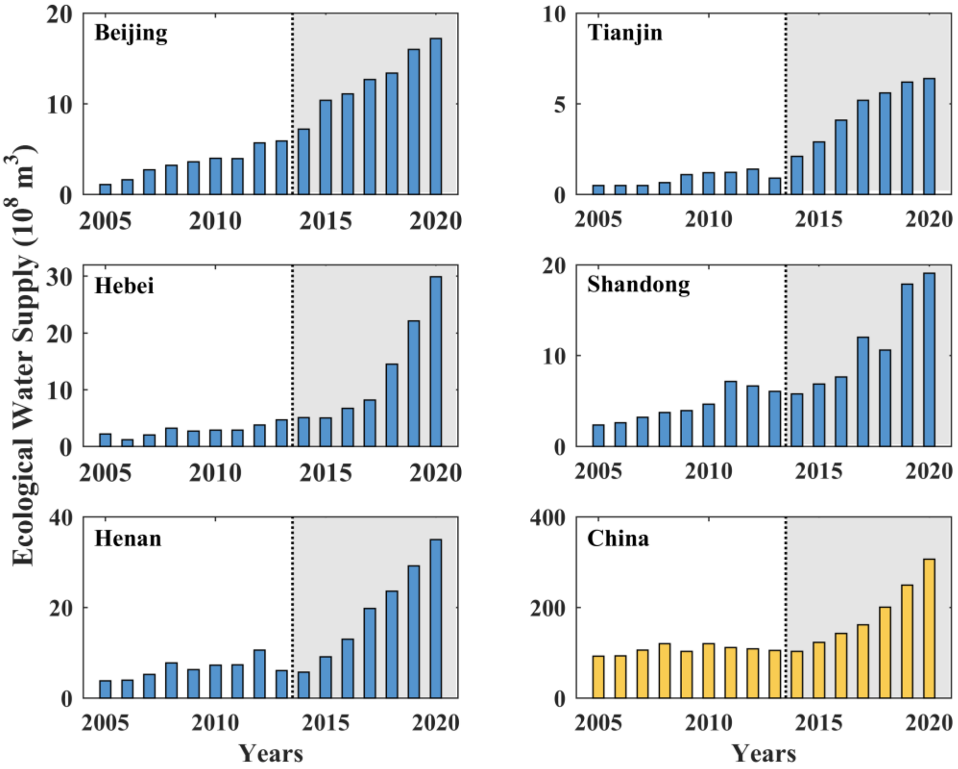

Figure 6 Ecological water supplies in China and the water-receiving area of the South-to-North Water Diversion Project (SNWDP)

3.3 Re-defining the demand-side management of a long-distance water diversion project

The various needs of national water managers, water diversion operators, and stakeholders in both water-donating and water-receiving areas are managed in an integrated manner by the SNWDP under the co-governance framework proposed in this study. To do this, a three-tier governance structure was established in this study, as shown in Figure 7. At the top level, as the national water administrative department, the Ministry of Water Resources is responsible for the supervision and macro prudential regulation of the project. At the second level, the South-to-North Water Diversion Group Corporation and its affiliated East Route and Middle Route companies are responsible for the water supply and the utility asset management. At the user level, the provincial governments in the water-receiving area purchase, receive, and allocate the transferred water to the end users. This structure covers the need for good governance at the national level, the requirements for the continuous operation of water supply companies, and the water demand of users(Pohlner, 2016).

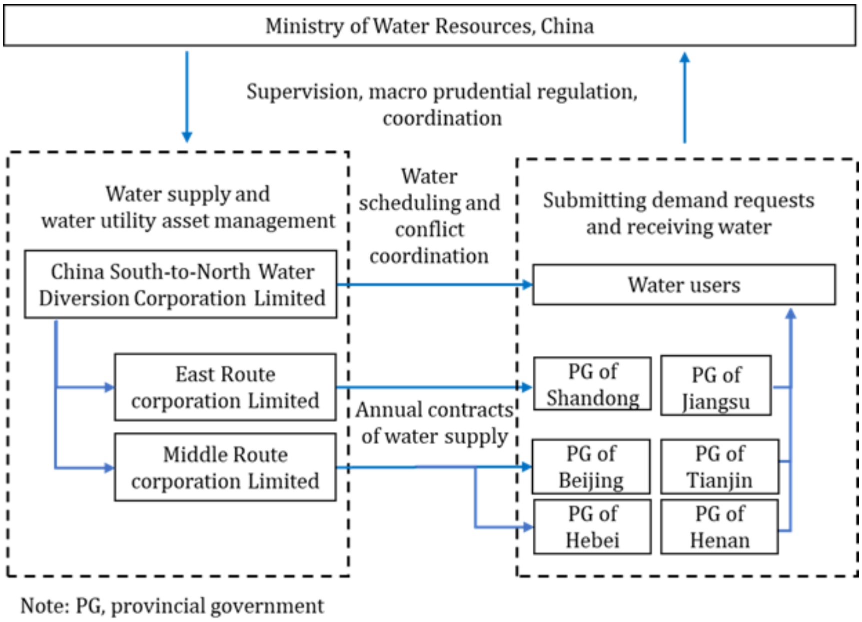

Figure 7 Three-tiered governance structure of the South-to-North Water Diversion Project (SNWDP)

The process of water transfer through the above three-tiered structure is as follows. First, the Ministry of Water Resources collects the annual water demand from the provincial governments in the water-receiving area before the water transfer at the beginning of each year. Afterward, representatives of the Ministry of Water Resources, managers from the water transfer corporations, and water users propose a planned volume of water supply for each region in the water-receiving area through negotiations in a formal meeting, in which the hydrological forecast for the upcoming year, the water delivery capacity of the infrastructure, and the water demand of users are generally used for planning. In this process, the participation of the Ministry of Water Resources in the water allocation negotiation embeds China's national will for the good governance of water and the national requirements for water conservation into the practical operation of the SNWDP.

After the allocation, the South-to-North Water Diversion Group and its subsidiaries sign water supply contracts with the provincial governments before supplying water and levying water charges. In addition, the South-to-North Water Diversion Group company is also responsible for adjusting the water scheduling on a monthly and real-time basis according to the actual water availability along the route. Each user in the water-receiving area should fully obtain their allocated volume of water at the end of year through the operation of the project. In the above process, the macro interventions from the central government and the practices of the company provide an advanced governance paradigm that includes both a limited public government and a limited market for the commercialization of the transferred water under a non-privatized water rights system. Effective interactions between the government and the market promote the efficient operation of the SNWDP.

At the user level, the provincial governments, on behalf of water users within the regions, submit applications to the central government for water supplies at the beginning of the year. The provincial governments can also apply for adjustments to their annual water allocations if changes in hydrological conditions occur during the year.

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This three-tiered governance structure inspires a paradigm shift for the demand-side management of a long-distance water diversion project through incorporating the consumptive demands of water users with the political and financial needs of the central government and the water supply enterprise, leading to more implementable and mutually recognized collective actions for effective water diversion (Eberhard et al., 2017; Wesselink et al., 2011).

4. Discussion

A co-governance framework is proposed in this study for sustaining the SNWDP in the long run. This framework adopts a broader view of water demand management through integrating the political, financial, and consumptive needs of the government, the market, and the users in the form of collaborative governance coupling both supply-side and demand-side solutions. The adoption of this framework would provide a more comprehensive understanding of the benefits and the necessity of the SNWDP in China and help inform practical strategies for the sustainable operation of the project in a changing environment.

4.1 Relationship between water demand and water price in water diversion projects

In the design of a water diversion project, the water price paid by the users is generally calculated according to the costs of project construction and operation, which depend on how large the project is and how much water it is expected to supply (Dinar and Subramanian, 1998). The volume of water supply is designed according to the estimated water demand. Ideally, the actual water consumption of the users is equal to the estimated demand, and the water fees paid by users can cover the cost of the project construction and operation.

In this study, the water price of the SNWDP was designed following this presupposition. The water price was divided into two parts based on the principle of covering fixed costs and variable costs in project operation, namely the basic water price and the metered water price (Table 2). The basic and metered water price can be calculated by apportioning the fixed costs and the floating costs of the project to users, respectively (Peng and Li, 2022). In the process of water fee collection, the basic water fee is charged based on the planned volume of supply estimated in the project design stage, and the metered water fee is charged according to the actual water consumption in a year.

Table 2 Water price adopted in the East Route and the Middle Route of the South-to-North Water Diversion Project (yuan/m³)

	Water price in the East Route				Water price in the Middle Route			
	Sub-sections	Basic	Metered	Total	Sub-sections	Basic	Metered	Total
1	South of Nansi Lake	0.16	0.20	0.36	Source area	0.08	0.05	0.13
2	Xiaji Lake	0.28	0.35	0.63	Nanyang Section of Henan Province	0.09	0.09	0.18
3	Shangji Lake to Changgou Pumping Station	0.33	0.40	0.73	Southern part of the Yellow River, Henan Province	0.16	0.18	0.34
4	Changgou Pumping Station to Dongping Lake	0.40	0.49	0.89	Northern part of the Yellow River, Henan Province	0.28	0.30	0.58
5	Dongping Lake to Qiutun Sluice	0.69	0.65	1.34	Hebei Province	0.47	0.50	0.97
6	Qiutun Sluice to Datun Reservoir	1.09	1.15	2.24	Tianjin Metropolis	1.04	1.12	2.16
7	East of Dongping Lake	0.82	0.83	1.65	Beijing Metropolis	1.12	1.21	2.33

Note: The Middle Route will release ecological water when the following conditions are met: (1) there are adequate inflows in the water-donating area; (2) the domestic, agricultural, and industrial water demand on the transferred water can be fully supplied; (3) the basic water fee is fully paid by the water-receiving area. The price of ecological watering is changeable and is determined through negotiations between the Middle Route corporation and the government in the water-receiving areas, with reference to the existing water price for domestic and economic uses.

There is an inherent problem with this pricing system in that the estimated water demand or planned water supply in the project design stage is not equal to the actual water demand. This is because the actual water demand of users can be influenced by numerous factors, including the weather, water rates, people's income, the marginal benefits of water-saving, and other psychological factors such as individual attitudes and beliefs regarding water conservation (Manouseli et al., 2019). These influencing factors are highly diverse and complex in different nations (Kamali et al., 2022), leading to the inaccurate estimation and in most cases overestimation of actual water needs when planning water supply projects. Consequently, numerous projects worldwide have become unprofitable “white elephant projects” whose upkeep costs outweigh the revenues they create due to the overestimation of the actual demand in the project design (Ganuza and Llobet, 2020). For example, the Binningup desalination plant in Western Australia was shut down within a year after its completion, although it was once regarded as the best solution to the water shortage in the local area. The plant was shut down because the high water price, which was caused by the huge construction cost of

2.3 billion Australian dollars, exceeded the user's willingness to pay, leading to insufficient water use and water fees to cover the costs (Radcliffe and Page, 2020).

Changes in the actual water demand have also occurred in the water-receiving area of the SNWDP. The annual mean water use of Shandong Province from the SNWDP has only reached 54% of its planned demand, although Shandong is a major water user of the East Route. One reason for this is that the marginal benefits of using transferred water are not high enough to outweigh the water price paid by Shandong's traditional industries to the SNWDP. The willingness to use the transferred water in Shandong Province is suppressed by high water prices. On the contrary, in the Middle Route, the water use of Beijing and Tianjin has already reached the planned volume because of the strong willingness to use the transferred water in their advanced industries, which have relatively high marginal benefits.

Further efforts are required to improve the water pricing system of the SNWDP through re-investigating the interactions among the water price, the actual water demand of users, and the costs of maintaining the project in the context of a changing environment. Specifically, for the East Route, research should focus on how to reduce the operation costs through reducing the electricity expenses, as the electrical consumption of water pumps accounts for a major portion of the cost of the East Route. Recent research on water–energy interactions could provide potential solutions for this (Liu et al., 2023). In addition, for the Middle Route, more research might be required on increasing the water price. Possible methods to increase the water price include tiered pricing structures (Smith, 2022; Sahin et al., 2018), block tariffs (Ruijs et al., 2008), and peak/ladder pricing systems (Molinos-Senante, 2014; Ben Zaied and Binet, 2015), through which the project could more effectively balance the water supply and the growing demand, especially during drought or during the peak season of water use.

4.2 Human water demand reduction, active environmental watering, and climate change

It is widely known that there is relatively more rainfall in southern China and less in the north (Day et al., 2018). There are abundant water resources in the Yangtze River Basin, but the Yellow River Basin and the Haihe River Basin in the north are short of water. However, since 2020, southern China has experienced severe droughts, while heavy precipitation has increased in the north (Zhang et al., 2022). For example, Dongping Lake, which is the northernmost water storage site in Shandong Province on the East Route, is supposed to receive the transferred water from the south. However, the Dongping Lake storage site had to release water back to the south along the route in 2021 due to extreme flooding inflows from the upper Yellow River and heavy rains in the local area. This increased the uncertainty regarding the sustainability of the SNWDP.

The demand for water from the SNWDP would decrease in the case of increasing rainfall and water availability in the water-receiving area due to climate change. Users will prefer relatively cheaper local water to the transferred water from the south if there is sufficient water in local storage. This is demonstrated in Figure 8, which shows the amount of water diverted from the SNWDP in Shandong Province, the average rainfall in the province, and the water storage of Dongping Lake since 2014. It can be seen that the water supplied from the SNWDP continuously decreased as the annual rainfall and water storage increased after 2017.

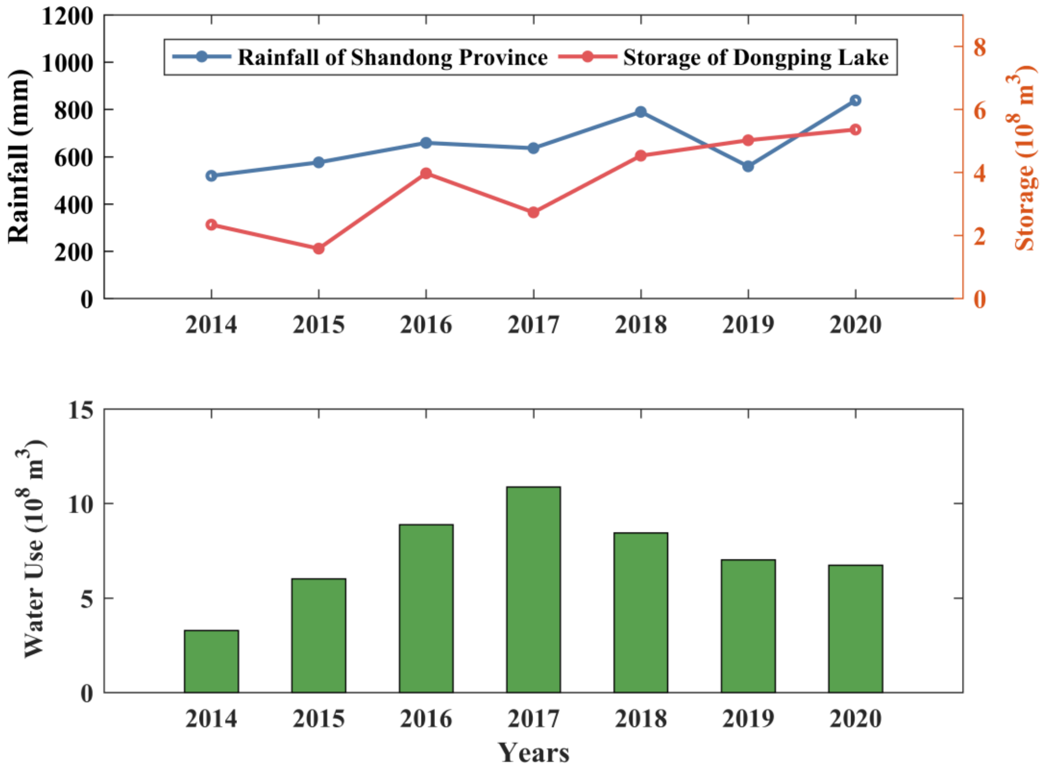

Figure 8 Changes in water diversion, rainfall, and water storage in Shandong Province

In response to the reduced demand, the SNWDP has released excess transferred water into northern ecosystems in the wet season, including the river courses and the Beijing–Hangzhou Grand Canal, leading to the significant recovery of environmental and navigational flows in rivers and canals, which are mentioned above. Releasing excess water in the rivers or lakes in wet seasons could, to some extent, reserve water for ecosystem uses in dry seasons when the water availability is limited. In addition, ecological water replenishment contributes to the restoration of wetlands and riparian habitats through increasing high flow pulses in environmental flow regimes. Similar practices are also adopted by other countries in the active management of environmental water, in which the water managers actively release water from storage to improve the volume, timing, and location of environmental water in real time (Horne et al., 2018).

Currently, releasing water to ecological systems is only a temporary seasonal arrangement in the SNWDP. The transaction costs of this practice are relatively high because negotiation between water transfer managers and water users is necessary to reach agreement on the proper volume and timing of the water release. Institutionalized regulations or rules are required to sustain this active management of environmental and cultural water by reducing the administrative and negotiatory expenses.

4.3 Impact of changes in water demand on the operation of water supply utilities

In 2022, the superior administrative unit of the South-to-North Water Diversion Group changed from the Ministry of Water Resources to the State-owned Assets Supervision and Administration Commission of the State Council, China. This change represented a major institutional reform that drove the South-to-North Water Diversion Group to shift its focus from water supply to capital management, that is to say, the South-to-North Water Diversion Group was required to further increase its revenue streams through broader business activities in addition to water charges. To meet this requirement, the South-to-North Water Diversion Group has established several business subsidiaries that are expected to gain benefits from developing smart water grids, water treatment, and investments in renewable energy.

However, this reform only began in 2022. The main source of the South-to-North Water Diversion Group‘s income is still water charges. Unfortunately, as mentioned above, the relatively high water price and increasing precipitation in northern China have reduced the willingness of water-receiving areas to use the transferred water, leading to the reduction of project revenues. The annual water use of the transferred water in Shandong Province has only been 54% of its planned demand/supply. Insufficient water uses and unprofitable revenues are critical issues impeding the long-term operation of the project.

One of the limitations of the South-to-North Water Diversion Group in gaining more benefits through developing a wider range of resources is that the major responsibility of the company is limited to the maintenance and operation of water transfer infrastructure on the routes (the red lines in Figure 3), excluding the management of rivers, lakes, and supplemental channels in the water-receiving areas. It is argued in this study that engaging in the economic development of water-receiving areas is a potential strategy to alleviate this problem. The effectiveness of this strategy is supported by the case of the Tennessee Valley Authority (TVA) in the United States, which is not only responsible for the construction and operation of water conservancy infrastructure but also gains benefits from electricity production as well as land and tourism development. This wide range of business activities provides a strong incentive for sustainable watershed management by increasing the revenue streams of the TVA (Kline and Moretti, 2014). However, it is still difficult for the South-to-North Water Diversion Group to further expand its business activities under the complex central–local relations in China. The current institutional arrangement in China allows the central government to formulate policies, laws, and regulations at the national level, while these policies are implemented by local governments in the daily affairs of their communities. This relationship is marked by a delicate balance of power between the central and local governments. The SNWDP Group, as a state-owned enterprise, is not supposed to dominate the utilization of water resources and the related economic activities of local communities in a top-down administrative manner.

Given the above factors, a potential viable alternative for the SNWDP Group to solve its current financial dilemma is to collaborate with local governments in water-receiving areas with the aim of increasing the economic benefits of the transferred water. The potential increase of the project revenue resulting from the increase of overall benefits through a more cooperative water resource development between local governments and the state-owned enterprise at the upper national level could be justified by the cooperative game theory of economics. According to this theory, the coalition can obtain the highest joint payoff for all players if participants can negotiate binding contracts that allow them to work together to achieve the best joint outcome. Through collusive strategies, the overall return of the coalition is greater than the sum of the returns of each member operating separately. In addition, the benefits obtained by each participant are never less than the benefits of not joining the coalition (Parrachino et al., 2006).

This cooperative game theory might help develop effective strategies for increasing the sustainability of the SNWDP through building a coalition that includes the water transfer enterprise, the local government, and the end users. Specifically, in this coalition, it is suggested that the South-to-North Water Diversion Group could participate in local economic development activities through capital injections in the form of water rights buyback or directly offering loans to the local government. Further research is required to develop practical solutions for increasing and sharing the overall returns between the SNWDP Group and local governments.

5. Conclusion

A new co-governance framework coupling supply-side and demand-side solutions toward sustainable water management in a changing environment was established in this study by advancing the traditional water demand management through literature reviews and a case study of the SNWDP in China. The proposed framework helps unpack the relationship between supply-side and demand-side management through casting light on the ecological benefits and revenue dilemma of a long-distance water diversion project in the context of climate change and changes in human water demand.

The case study shows that the SNWDP is not simply a supply-side engineering measure but a combination system of both supply-side and demand-side management if it is evaluated in the context of China's national water conservation polices. In addition, it is found that there is increasing uncertainty in regard to the sustainability of the project caused by the potential water demand reduction in the water-receiving areas, where the local rainfall and water availability have increased recently and the users' willingness to utilize relatively expensive transferred water is decreasing. This directly leads to insufficient revenue to cover the operational costs of the project, and this has already challenged the sustainability of the project.

A set of strategies were provided for increasing the sustainability of the SNWDP based on the framework proposed in the study. First, changes in the actual water demand for the transferred water in the water-receiving area should be evaluated with various water price levels. Based on this, a more affordable water price that can incentivize the use of transferred water can be applied. Second, a long-term institutional arrangement for actively leasing ecological water from the project in the wet season is required in the context of reduced human water demand. Third, sufficient revenue is also required to cover the costs of maintaining the active environmental water management methods mentioned above. Collaborative strategies are recommended in this study for the SNWDP Group to increase its profitability by participating in the economic development of riparian regions on the water transfer routes. The proposed framework and strategies based on the experiences of the SNWDP are also valuable for other water diversion projects around the world whose sustainability is challenged by the contradiction between the need to increase revenues to cover operational costs and the possible reduction of water demand caused by climate change, high water prices, and economic depression.

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Author contributions

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The contact author has declared that none of the authors has any competing interests.

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