# 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.

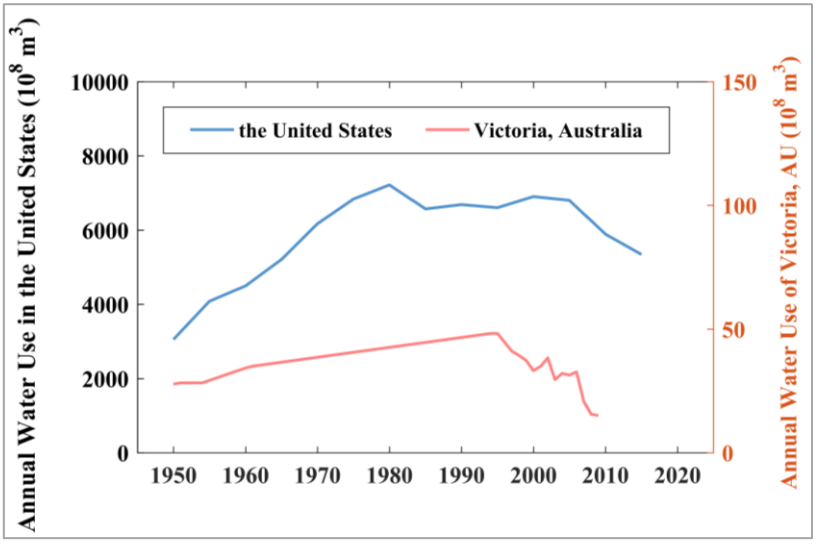



**Figure 1 Annual water use in the United States and in Victoria, Australia**

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 analysing its paths towards the sustainability, including several strategies including reducing energy expenditures, reforming water pricing, and expanding the scope of negotiation and cooperation, considering the uncertain trajectory of water demand in the receiving regions. This study provides innovative insights on the interaction between supply-side and demand-side solutions within the case project, in particular establishing a new co-governance framework to sustain the water supply system in the case of uncertain environmental changes.

## 2. Material and methods

### 2.1 Methods

A co-governance framework was established to enhance 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 nexus 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 variability 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 assessed 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.

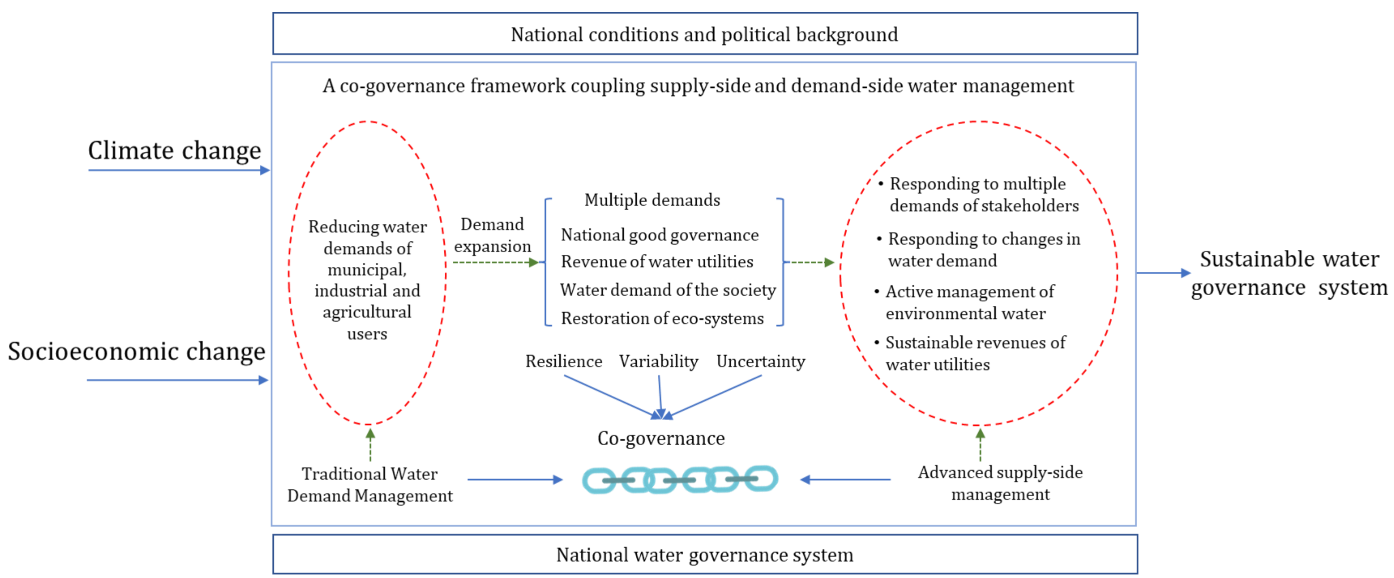



**Figure 2 Co-governance framework coupling supply-side and demand-side solutions toward sustainability**

## 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.

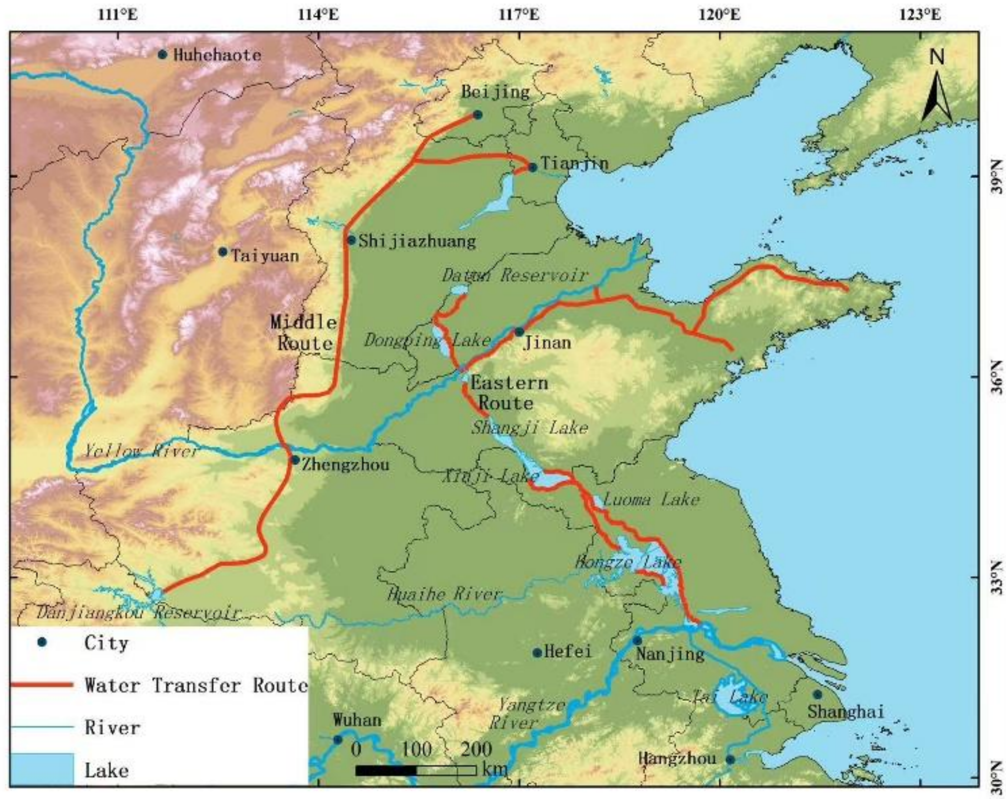



**Figure 3 East and Middle routes of the South-to-North Water Diversion Project (SNWDP)**

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, a comprehensive assessment of the SNWDP are conducted in this study using the proposed co-governance framework in a wider perspective of sustainable water demand management, focusing on the interplay among political dynamics between national and regional government and financial constraints of the project maintenance, as well as how these collectively impact the effectiveness of the SNWDP. Detailed analysis is provided on how the proposed framework facilitates cooperations among different government entities, policymakers, and businesses related to the operation of the SNWDP to ensure its alignment with national political objectives, legal regulations, and ecological conservation actions.

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); (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.

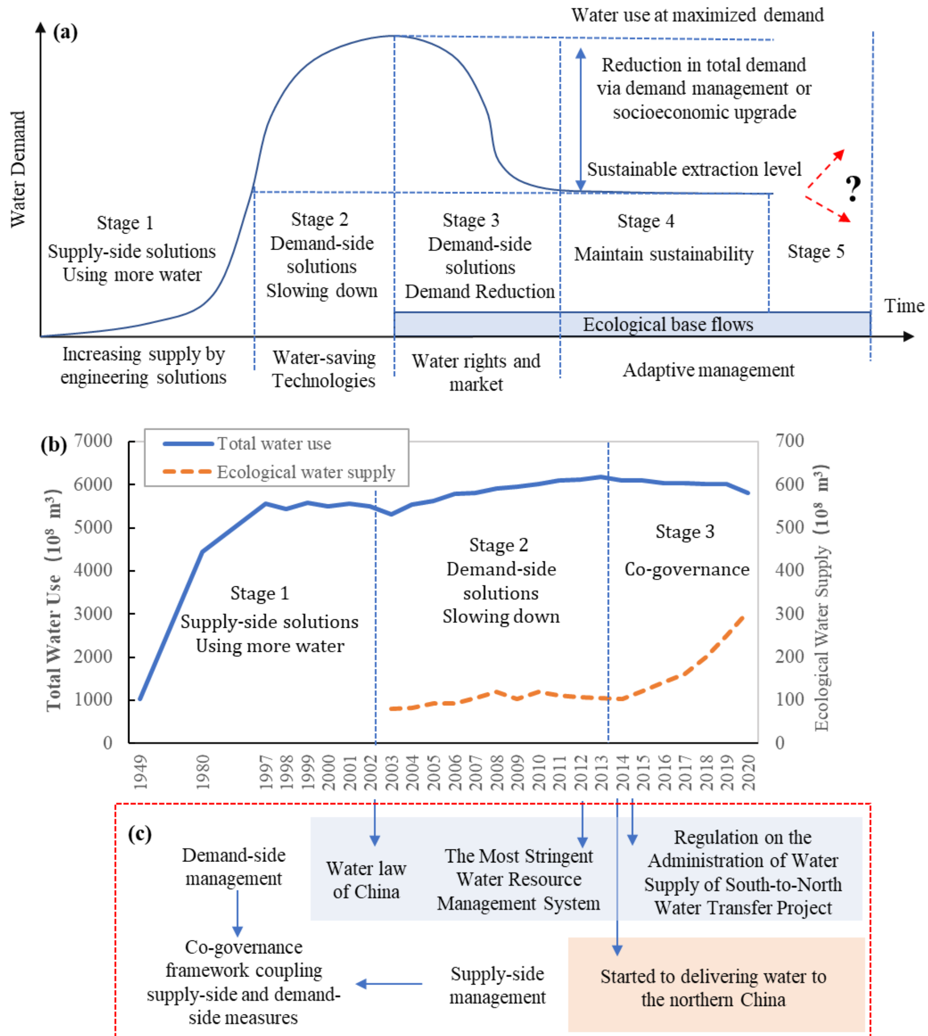



**Figure 4 Co-governance of the water demand and supply of the South-to-North Water Diversion Project (SNWDP)**
**Note: Figure 4(a) represents the stages of water demand change, sourced from Lochetal.,2020; Figure4(b) shows the changes of total water use and the ecological water supply in China; Figure 4(c) shows the polices for water demand management in China**

### 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.

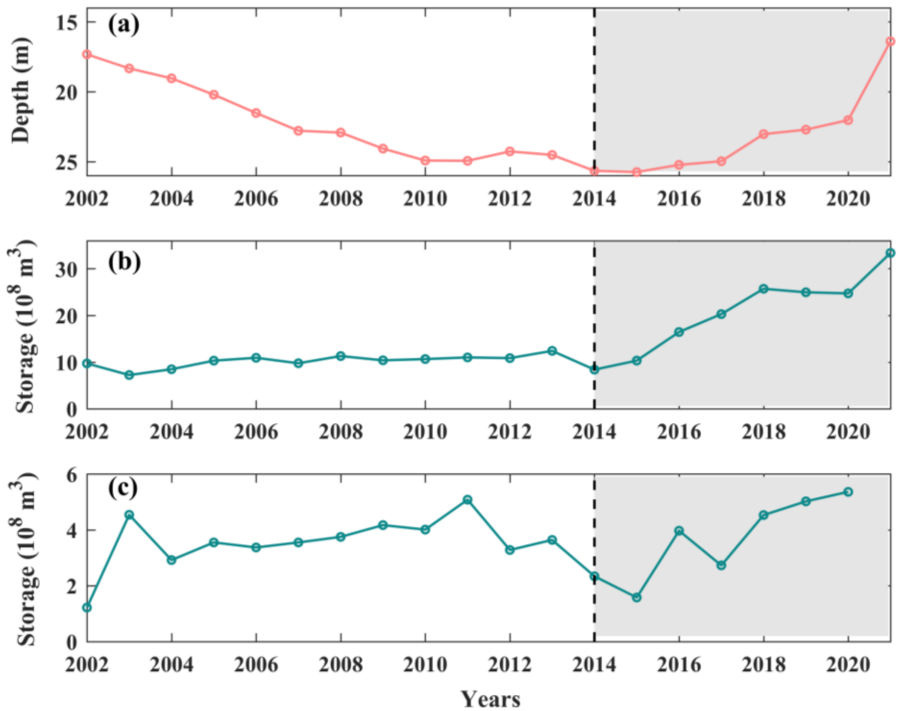



**Figure 5 Impact of the South-to-North Water Diversion Project (SNWDP) on ecosystems in the water-receiving area**
Note: Figure5(a) shows the interannual variation of groundwater depth in the North China Plain; Figure 5(b) shows the interannual variation of the water storage in the Miyun Reservoir; Figure 5(c) shows the interannual variation of the water storage in Dongping Lake.

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).

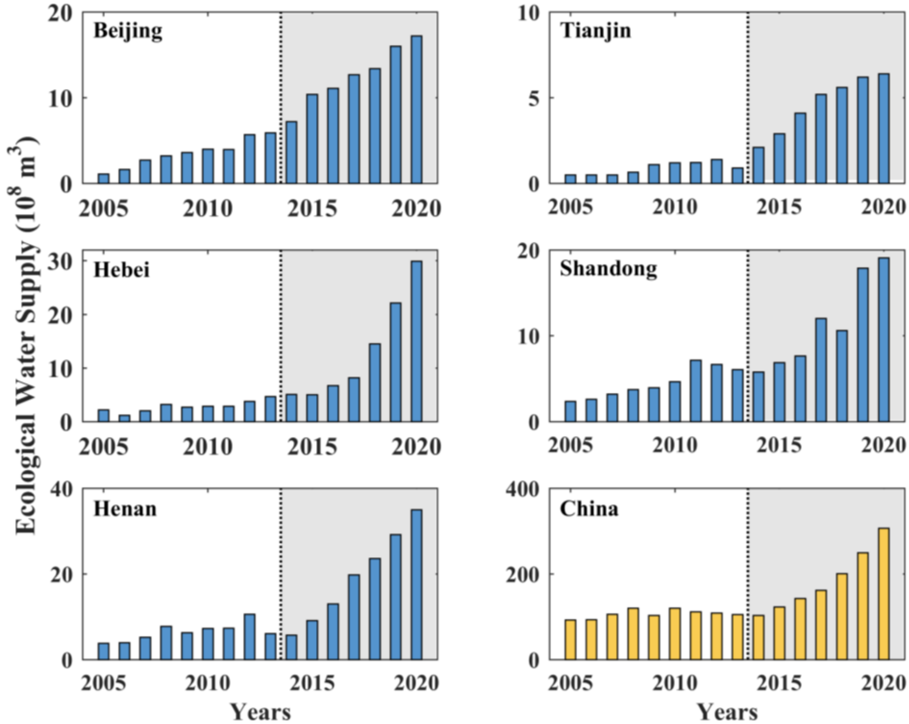
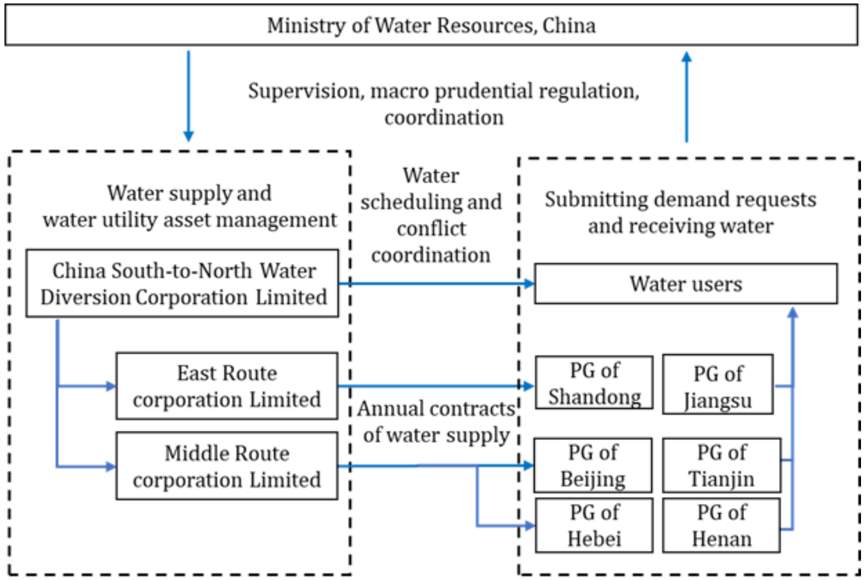



**Figure 6 Ecological water supplies in China and the water-receiving area of the South-to-North Water Diversion Project (SNWDP)**

### 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 are 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).




Note: PG, provincial government

**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.

Every three years, the South-to-North Water Diversion Group and its subsidiaries enter water supply contracts with provincial governments. According to these agreements, the Group and its subsidiaries collect a portion of the water charges in advance each year before commencing the water supply, with the remainder being collected after the completion of the water supply period in the year. 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. 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.

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

In this section, practical strategies aimed at mitigating the challenges associated with sustaining the South-North Water Diversion Project (SNWDP) are discussed. Firstly, strategies to reduce operational costs are discussed, focusing on the project's electricity consumption. Reducing energy expenses is pivotal for enhancing the project's sustainability. Additionally, we propose a flexible water pricing system to enhance the sustainability of the SNWDP by underscoring the effectiveness of economic analysis within the proposed supply-demand co-governance framework. Basing on this, an equitable distribution of water diversion costs between users and the government are discussed, aiming to enhance the project's economic viability and social acceptability. Furthermore, we examine the role of the SNWDP in mitigating water supply uncertainties under climate changes. The insights from these discussions could provide practical recommendations for sustaining the SNWDP, and serving as a reference for the sustainable development of other large-scale water transfer initiatives.

### 4.1 Implementing energy efficiency solutions towards sustainable operations in the SNWDP.

In this study, we address the critical challenge of sustainability in large-scale engineering projects, with a particular focus on the SNWDP in China. A global trend has emerged where numerous expansive water projects become economically unfeasible, often labeled as "white elephant projects" due to their disproportionate costs and marginal returns (Ganuza and Llobet, 2020). A notable instance is the Binningup desalination plant in Western Australia, which ceased operations within a year of completion. Initially seen as a vital solution to local water shortages, the plant's shutdown was precipitated by a pricing system that failed to align with user affordability, a consequence of its hefty 2.3 billion Australian dollar construction costs (Radcliffe and Page, 2020).

For the SNWDP, a project underpinned by significant construction and operational expenditures, achieving a balance between costs and revenues is critical for its sustainability. The project's water pricing strategy, designed to cover both fixed and variable operational costs, consists of two components: a basic water price and a metered water price, as detailed in Table 2. These prices are calculated by distributing the project's fixed and variable costs to users, respectively (Peng and Li, 2022). In practice, the basic water fee is levied based on the planned supply volume, while the metered fee aligns with actual annual consumption.

However, a notable discrepancy exists between the planned demand and actual demand. For example, in the SNWDP's eastern route, Shandong Province's actual water consumption is only 54% of the anticipated demand. This shortfall is primarily due to the traditional industries in Shandong figuring out the marginal benefits of using transferred water insufficient to justify the cost. Consequently, research should pivot towards operational cost reduction strategies to reduce the water prices, particularly focusing on electricity expenses, a significant component of the East Route's costs. Insights from recent studies on water-energy interactions may offer viable solutions to this issue (Liu et al., 2023).

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

| No. | 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.

## 4.2 Economic and social strategies to enhance the sustainability of the SNWDP.

### (1) Reevaluating supply-demand coupled water resource management strategies: an economic perspective.

Section 4.1 delves into a pivotal issue encountered during the initial phase of the SNWDP: the excess water supply in the eastern route, juxtaposed with the contrasting scenario of water scarcity and operational strains in the middle route. This phenomenon primarily stems from an inadequate economic assessment of water resource demand in the project's planning stage, resulting in a supply-demand imbalance. Addressing this disparity necessitates a thorough economic analysis of water demand in the recipient regions. Economic theory on demand elasticity elucidates the dynamic interplay between price and demand, suggesting that users' water demand fluctuates based on their financial capacity and willingness to pay. For instance, higher water prices may lead users, especially those with limited economic capacities, to curtail their consumption, thereby impacting regional water resource demand. Simultaneously, the marginal cost principle provides an additional lens, underscoring the requirement for water prices to mirror the cost of delivering an incremental unit of water. In the realm of water resource management, this implies that pricing strategies should extend beyond mere cost recovery to encompass market demand sensitivity. An optimal pricing strategy would strike a delicate equilibrium, covering the marginal costs of water resources while also accommodating diverse user responses to price shifts. Such an approach would contribute to harmonizing supply and demand, facilitating efficient water resource allocation, and bolstering the project's economic viability. Therefore, by conducting an in-depth examination of the correlation between water prices and demand, water supply strategies can be fine-tuned to better cater to the distinct requirements of various regions and their water users.

**(2) Developing a practicable cost-sharing mechanism**

Given the intricate and multifaceted nature of the South-to-North Water Diversion Project, which encompasses the interests of industrial, agricultural, urban stakeholders, and the ecological environment, the development of an equitable and efficient cost-sharing framework is imperative. It necessitates a detailed quantitative assessment of the economic, social, and ecological benefits derived from the diverted water. This encompasses the evaluation of direct economic advantages for industrial, agricultural, and urban residential users, such as enhanced production efficiency and an improved standard of living. Furthermore, it is essential to consider the project's positive externalities, including potential increases on regional economic developments and environmental improvements like water quality enhancement and ecosystem restoration. Basing the comprehensive assessment of the benefits of the project, a multi-stakeholder cost-sharing scheme should be proposed following the principle of "beneficiaries pay", which considers the varying payment capacities and socio-economic conditions of different water uses.

A proportional cost-sharing model could be employed, where industrial, agricultural, and urban residential users contribute according to the direct benefits accrued. Additionally, the positive economic and environmental externalities of the water diversion might surpass the immediate advantages for individual users. In this case, local governments could assume responsibility for a segment of these positive externalities, mirroring their long-term commitment to societal and environmental well-being. Furthermore, responsibilities of cost sharing at the national level for ecological restoration and other broader societal advantages, which are characterized by their universal and enduring nature, should be managed by the central government.

**(3) Multi-party participation, negotiation, and cooperative gameplaying**

Multi-party participation, negotiation, and cooperative game playing is essential for the SNWDP's sustainability. Their significance is underscored by the diverse stakeholders involved in the operation of the project and the innovative, comprehensive, and efficient solutions that such participation fosters to enhance the sustainability. For example, a significant development in 2022 was the transition of the project's senior management from the Ministry of Water Resources of China to the State-owned Assets Supervision and Administration Commission of the State Council. This shift signifies a move from a narrow focus on water supply to a broader perspective on capital management, emphasizing the need for collaborative approaches with water-receiving regions.

In a multi-party water resource management framework, cooperative game playing is effective as it encourages stakeholders to transcend traditional zero-sum perspectives in favour of mutually beneficial outcomes. For the SNWDP, this involves not only maximizing the efficiency of the transferred water but also leveraging the project to drive regional economic growth, enhance environmental quality, and improve social welfare. Strategies such as joint ventures between water supplying entities and receiving regions, including water rights buybacks, joint investments, and collaborative infrastructure development, are instrumental. These strategies aim to maximize the economic utility of the transferred water and amplify the project's overall impact.

### 4.3 Re-thinking the impact of climate change on the sustainability of the SNWDP.

Historically, Southern China has been characterized by higher rainfall intensities compared to its Northern counterpart. However, recent climatic shifts have upended this pattern, with the South experiencing frequent droughts and the North receiving increased rainfall. This alteration has significant implications for the water demand dynamics of the SNWDP. The rise in local water availability in the North, due to increased rainfall, may lead to a preference for utilizing local, lower-cost water sources over the transferred water from the South. This trend is evidenced by the decreased reliance on the SNWDP since 2017, coinciding with heightened annual rainfall and increased water storage in Shandong Province's Dongping Lake, as shown in the Figure 8.

The primary driver behind this changing climate pattern might be the inter-decadal transition evident in the dipole pattern of annual precipitation between North and South China(Huang et al., 2023). Since the late 1970s, a southward shift in the rainfall centre resulted in prolonged droughts in Northern China. However, the recent northward migration of the rainfall belt has unexpectedly increased water resources in the North, exemplified by the extreme flooding of Dongping Lake in late summer 2021. This event hindered the lake's ability to receive the anticipated water volume from the SNWDP's eastern route, leading to flood discharges through the Yellow River and eastern water transfer route.

Amidst the climate change, this abnormal abundance of water resources in the North remains highly variable and potentially ephemeral. Long-term projections suggest that Northern China may continue to experience recurring droughts. Consequently, despite the current temporary surplus of water in the North, the SNWDP remains crucial for mitigating water scarcity and drought risks in the region. Future water resource management strategies must incorporate the uncertainties of climate change, adopting flexible and adaptive approaches to address potential fluctuations. This requires preparing for scenarios of both excess and shortage, ensuring that the SNWDP can effectively respond to the unpredictable nature of climate impacts on regional water availability.

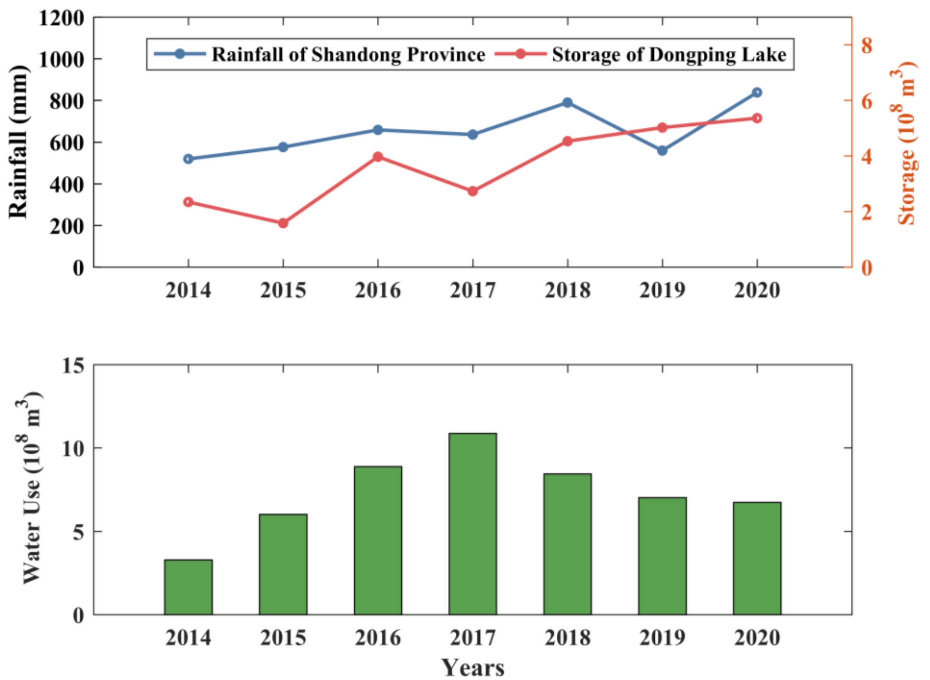



**Figure 8 Changes in water diversion, rainfall, and water storage in Shandong Province**

## 5. Conclusion

A new co-governance framework coupling supply-side and demand-side solutions toward sustainable water management in a changing environment is established in this study by advancing the traditional water demand management through literature reviews and a case study of the SNWDP in China. 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. This project considers not only the allocation and distribution of water resources but also addresses long-term water resource management and ecological protection needs amid significant environmental challenges like climate change. From a broader perspective of national governance, the SNWDP exemplifies a model of collaboration among the government, consumers, and operators. It effectively demonstrates the combined role of proactive government intervention and market mechanisms in public resource allocation, highlighting the importance of balancing interests and responsibilities among various stakeholders in large-scale public projects. The proposed the framework underscores the significance of integrated governance strategies in ensuring the sustainable utilization of water resources by analysing the multifaceted impacts of the SNWDP. It could provide insights that could be applicable to other large-scale infrastructure projects worldwide, particularly those facing similar challenges in balancing operational costs, environmental impacts, and the evolving needs of diverse stakeholders.

Building upon this understanding, current challenges faced by the SNWDP are discussed, with a particular focus on the financial difficulties stemming from supply-demand imbalances. The impact of reducing energy expenditures and operational costs on enhancing the project's sustainability is also analysed. Additionally, this study explores the implementation of a flexible water pricing system, integral to the proposed co-governance framework, and stresses the necessity of economic analysis in this context. As a result, the equitable distribution of water diversion costs between users and the government is proposed, aiming to augment the project's economic viability and social acceptability. This comprehensive analysis not only offers practical and insightful recommendations for the SNWDP but also provides valuable guidance for other large-scale initiatives, promoting broader sustainable development practices.

## Acknowledgement

This study was financially supported by the National Natural Science Foundation of China (U2040206)，(52179009) and (51909035)

## Author contributions

Yueyi Liu: Data curation, Writing- Original draft preparation, Visualization; Hang Zheng: Conceptualization, Methodology, Investigation; Jianshi Zhao: Supervision, Validation, Writing- Reviewing and Editing.

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