water

Review

China's South-to-North Water Diversion Project: A Review and Reach Beyond China's Borders

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Abstract

The South-to-North Water Diversion Project (SNWDP), the world's largest water transfer initiative, is designed to address northern China's acute water scarcity by diverting approximately 45 km^3 of water annually from the south through three major routes, with completion targeted for 2050. This review demonstrates that the SNWDP has already improved water security for over 150 million people, stabilized groundwater, and supported agricultural and urban development, but also presents significant challenges, including escalating costs, large-scale resettlement, and substantial environmental concerns such as ecosystem alteration, salinity intrusion, pollutant transfer, and risks to biodiversity and water quality. While mitigation and adaptive management efforts are ongoing, their long-term effectiveness remains uncertain. Notably, the SNWDP's influence extends beyond China: by enhancing food production self-sufficiency, it can help stabilize global food markets during concurrent droughts and serves as a model—albeit a debated one—for large-scale water management and governance. The project's hydropolitical and geopolitical dimensions, especially regarding the planned western route and potential transboundary impacts, underscore the need for international dialog and monitoring. Overall, the SNWDP exemplifies both the opportunities and dilemmas of 21st-century megaprojects, with its legacy dependent on balancing economic, environmental, and social trade-offs and on transparent, participatory governance to ensure sustainable outcomes for China and the global community.

Keywords: hydraulic mission; hydropolitics; water wars; sustainability; transboundary water transfer; red flag river; global food security

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1. Introduction

Increasing populations and global climate change effects cause growing water scarcity and snowballing water demands in agriculture, industry, and urban areas [1,2]. Increasing water scarcity and regional differences in water supply have created a demand for large-scale water transfer [3–6]. Transboundary water transfer volumes have been estimated to beat 550 km^3 per year, corresponding to about 15% of the global water withdrawals globally [3,7,8]. By 2050, the total transferred water volume may constitute about half of the global water withdrawal (presently about 4000 km^3 per year) [3,9]. This is expected to significantly influence the global water cycle and related environmental and ecological conditions.

Recent years have seen an intensification of global water scarcity and drought, driven by climate change and increasing anthropogenic pressures. The Intergovernmental Panel on Climate Change (IPCC) highlights that the frequency and severity of droughts are rising, particularly in arid and semi-arid regions, with over 5 billion people projected to experience scarcity by 2050 [10]. The Food and Agriculture Organization (FAO) further reports that climate extremes are increasingly disrupting agricultural production and water availability, threatening food security on multiple continents [11]. Recent studies estimate that inter-basin water transfers already account for about 15% of global water withdrawals, and may reach up to 50% by mid-century, fundamentally altering the global water cycle and associated environmental conditions [1–3,12]. These trends underscore the urgency of developing robust, adaptive water management strategies and highlight the relevance of large-scale projects such as the South-to-North Water Diversion Project (SNWDP) in China.

The South-to-North Water Diversion Project (SNWDP) in China is presently the largest transboundary water project in the world in the Chinese context, e.g., [13–19]. At its completion stage in 2050, it is expected to transfer 44.8 km^3 water per year from more humid southern China to the large population in the drier north. Chairman Mao was the first in 1952 to propose transporting water from the south to the north to supply water to quickly growing cities and provinces like Beijing and Tianjin, Hebei, Henan, and Shandong [20–22]. The project was eventually initiated in 2002 with the aim of alleviating water scarcity in northern China, which is home to approximately half of the country's population and 15% of its arable land but only about 7% of its water resources. The project involves diverting water from the Yangtze River to the Yellow River through three separate routes: the eastern, central, and western routes. The SNWDP will link four of China's main rivers, namely, the Yangtze, Yellow River, Huaihe River, and Haihe River. The official total costs are USD 62 billion, corresponding to twice the total of the Three Gorges Dam. The central route serves the provinces of Henan and Hebei and the mega-cities of Beijing and Tianjin. The central route was launched in December 2014. The eastern route with its first phase started in November 2013, serving the provinces of Jiangsu and Shandong. The western and most controversial route is still in a planning stage. In early 2023, SNWDP had diverted over 60 km^3 of water corresponding to more than the average flow of the Yellow River (about 58 km^3 per year) [23].

By situating the SNWDP within this evolving global context, this review aims to provide a holistic assessment of its domestic and international significance, drawing on the most recent literature and data. This review aims to provide a holistic overview of the SNWDP and its history, status, international debate, and impacts. Analyses of the impacts and sustainability of the entire SNWDP are an enormous and almost impossible task, especially since the actual project costs are difficult to assess. Also, a substantial and mature body of journal articles on the hydropolitics, sustainability, economics, and ecology of the SNWDP already exists, e.g., the contributions from the Melbourne University water group [24,25]. The objective of this review and the main innovative aspects are to bring the attention of readers to the global aspects of the SNWDP. We believe that its effects reach far beyond China's borders. The regional and global effects of the SNWDP are to the authors' knowledge almost completely absent in published research except for the possible but unlikely transboundary Red Flag River project, e.g., [13,16,18,20,26–29]. We intend to show that the SNWDP has environmental, climatic, geopolitical, economic, and governance impacts on a global scale. In view of this, we first review published studies on domestic effects and debates of the SNWDP. After this, we attempt to discuss effects on the larger regional and international scale. This review discusses the project's economic and social aspects, as well as its environmental challenges, debates, and limitations. The review draws on a wide range of literature, including academic articles, government reports, and news articles. One of the direct effects of the SNWDP is on global food security. However, there are also other important indirect effects such as technology transfer, norms, and “exportable” governance models. China’s experience in engineering, tunnel and pumping tech, project financing, and institutional arrangements is becoming a part of a global toolbox (and an exportable model) for other countries building big water works or BRI-linked hydrological projects. These aspects are becoming increasingly important as China’s economic power increases. Accordingly, this paper first gives a historical and hydroeconomic account of the project. We then reflect on the domestic and international sustainability aspect of the project. After this, we look at the SNWDP from hydropolitical and geopolitical attributes and debate of the SNWDP. Consequently, this review forms a basis for an overarching global sustainability analysis of the SNWDP not just domestically for China but also with an important international perspective. We close with a summarizing conclusion. The literature search included in this review was performed using keywords related to the effects and sustainability of the SNWDP using Web of Science and Google Scholar, including SCI and SSCI indexed papers. We also used research reports, web sources, and news press articles up to 2025. Literature references in the collected publications were further used to widen the initial internet search. From these potential publications, we selected more than 130 pertinent publications to be included in the review, incorporating publications in Chinese (see References).

Accordingly, this paper first gives a historical and economic account of the project. Then environmental and social effects of the project are reviewed. After this, we look at the SNWDP from an international food security perspective in view of population and climate change. Consequently, this review forms a basis for an overarching sustainability analysis of the SNWDP not just domestically for China but also with an important international perspective. We close with a summary of discussion and conclusions.

2. Historical and Hydroeconomic Overview of the South-to-North Water Diversion Project (SNWDP)

Although the late chairman Mao Zedong, in modern times, proposed to “borrow” some water from the water-rich south (Yellow River) for the dry north (Beijing, Tianjin, etc.), hydraulic channels have a long history in China. The earliest parts of the Grand Canal (Da Yun He), now a UNESCO World Heritage Site, were first built in the 4th century BCE and rebuilt in 607 CE. It connects Hangzhou in Zhejiang Province with Beijing, and with its length of 1800 km, it is the world’s longest constructed waterway [30]. However, it was built not to transfer water but instead surplus grain from the humid Yangtze and Huaihe River areas to drier northern China. For the SNWDP, it took until August 2002 for the State Council to approve the start of construction and probably the help of water engineers turned politicians. The former Chinese Premier Li Peng was trained as a hydraulic engineer and retired Chinese President Hu Jintao was a graduate of Tsinghua’s Department of Water Conservancy [31].

The SNWDP, as the main backbone and artery of the national water network, bears the important mission of ensuring the security of the national water supply [32]. The SNWDP, as a major piece of strategic infrastructure of the country, is as an important key in optimizing the allocation of water, ensuring the safety of drinking water for the masses, restoring the ecological environment of rivers and lakes, and smoothing the economic cycle between the north and the south [33]. As mentioned above, the SNWDP is divided into three main routes: the eastern, central, and western routes (Figure 1). The eastern route starts at the major branch of the Yangtze River and runs through Jiangsu, Shandong, and Hebei Provinces before reaching Tianjin. The central route starts at Danjiangkou Reservoir in Hubei Province and runs through Henan, Hebei, and Beijing before ending in Tianjin. The planned western route starts from three tributaries in Yangtze River Basin close to the

Bayankala Mountain and connects to the Yellow River in Qinghai and Gansu Provinces to supply more water to Shaanxi, Shanxi, Inner Mongolia, and Ningxia Provinces.

It is well known that the idea of SNWDP has its root in a historical fascination among Chinese Communist Party leaders with the promise of hydraulic engineering [34] and its origin is attributed to Mao Zedong [35]. The project has therefore been accompanied by strong geopolitical power throughout the project's implementation, from its blueprint to decision-making. However, due to the lack of transparency throughout the decision-making, planning, and implementation processes, there has been very limited attention from Western scholars until recently.

Figure 1. The South-to-North Water Diversion Project (SNWDP) through its three routes: green—central; orange—eastern; and red—western (with permission from source: [36]).

The eastern and central routes became operational in 2013 and 2014, respectively (Table 1). However, work continues to adapt local water structures to the diverted water volumes. The western route is the most technically complex and expensive part and will probably not be in full operation until the project completion in 2050. Its diverted water volume may represent about 17 km^3 of water per year after completion. The average altitude for the western route varies between 3050 and 4000 m. An extension of this project is the controversial Red Flag River which could divert up to 60 km^3 water per year from the three transboundary rivers Mekong, Salween, and Brahmaputra [37–39].

Table 1. Hydroeconomic summary of the South-to-North Water Diversion Project (SNWDP) and its three routes.

	Estimated Transfer (km^3/Year)	Length (km)	Estimated Cost (USD Billion)	Operation (Year)
Total project	44.8	4350 [1]	62–120	2050
Eastern route	14.8	1155		2013
Central route	13.0	1267	37.44–81 [2]	2014
Western route	17.0	300	39.0	2050

Notes:[1] Includes main and auxiliary branches [40]. [2] Includes both eastern and central routes, lower official cost (USD 47 billion is mentioned by [28]) (USD 79.4 billion is mentioned by [41,42]) (USD 81 billion is mentioned by [43]).

The water intake of the east route is located approximately 300 km from the estuary of the Yangtze River, where Shanghai's drinking water sources are located [44]. Accordingly, the east route has had more intricate and unpredictable impacts on local aquatic environments compared with the middle route [44]. For the middle route, a highly protected water-conveyance canal has been established from the donor basin to the recipient basin [44]. Construction of the middle route of the SNWDP officially started on 27 December 2003; it was officially opened on 12 December 2014. As of 12 December 2023, the middle route of SNWDP has been fully operational for 9 years [45]. Costs involved in the SNWDP are not easy to assess. Official figures differ from figures mentioned in the literature. Official figures state about USD 62 billion for the entire project [40]. However, USD 79.4 billion has been mentioned for the completed eastern and central routes [41,42]. Besides direct project construction costs, the costs of evicting and resettling up to 375,000 people for the enlargement of Danjiangkou reservoir and construction of canals need to be added [41]. This could correspond to up to USD 6 billion. Besides these costs, China has started water conservancy projects valued at USD 60.3 billion [40]. These projects include pollution mitigation and other water conservancy projects involving the SNWDP as well. The full extension of the western route has not yet been officially disclosed due to its technical difficulty, but if it is realized it will probably likely be the most expensive part of the SNWDP (Table 1).

3. Sustainability of the SNWDP

The literature contains many reviews and summaries on large-scale water transfers. Commonly, water transfers to drier areas tend to induce water waste and increase further demand. On the sustainability scale, large water transfers tend to have both positive and negative effects depending on scale and period. Consequently, there are an immense number of multi-faceted aspects of sustainability (or unsustainability) that result from such megaprojects, e.g., [15,46–50].

3.1. Domestic Effects and Impact of SNWDP

Estimating the total costs of the SNWDP is difficult, making its economic sustainability uncertain, especially as the project is not yet complete. Two model estimations were discussed in [26] based on comprehensive data from [15]. The World Bank [51] found the project economically beneficial, while the World Wildlife Fund [52] did not. This is logical since large water projects often boost agricultural output but can negatively impact natural habitats and wildlife. The Chinese government has invested significant funds in mitigation, including treatment plants, pollution transport mitigation, and ecological zones (USD 60.3 billion in 2022 [53]). Assessing the effectiveness of these measures is challenging, but China has previously shown determination to address ecological concerns such as erosion, afforestation, and flooding, often with economic guidance [54–56].

The environmental sustainability of the project has been extensively studied [26]. For the eastern route, ref. [57] showed effects on Dongping Lake, including changes to soil, hydrology, and meteorology, though negative effects were judged less serious. The main negative effects of the middle route are inundation and major resettlements due to the Danjiangkou Dam and related canals and reservoirs on the North China Plain [58]. The western route affects a small population in the upper reaches of the Yangtze and Yellow Rivers and may have adverse environmental effects on the upper and middle reaches of the Tongtian, Dadu, and Yalong Rivers.

Major diversions from the Yangtze River will affect the river mouth and delta areas. These effects include both ecological problems and increased salinity levels in the river, affecting the ecosystem of the river and the surrounding wetlands, leading to risks for saline water intrusion, and increased erosion of coastal areas as pointed out by [22,59]. A substantial amount of water is withdrawn by the central route of the SNWDP, corresponding to about 35% of the Yangtze's flow at that point. On the positive side, the project has helped to alleviate water scarcity and sinking groundwater levels in northern China, especially in the Beijing and Tianjin areas. It has also reduced the risk of floods in the Yangtze River Basin by diverting excess water to other areas. The SNWDP is a significant addition to China's water reforms, providing more equitable water access and socioeconomic development in northern areas [60]. The authors of [61] convey a positive picture of improved environmental sustainability due to the SNWDP. For example, water scarcity in northern China has been predicted to account for a lack of about 30 km^3 by 2030, estimated to represent a USD 20 billion economic loss due to lack of grain production [61]. Another objective of the SNWDP is to prevent further groundwater drawdown in the North China Plain, which includes most of China's high-productive agricultural areas [62–65]. The agricultural dimension of the SNWDP is a major driver for the water transfer [66,67]. Agricultural analyses indicate that the SNWDP may increase agricultural value by more than 10% as an average [68]. More importantly, this means that food security for the entirety of China increases significantly for the at-present 150 million people in northern China who benefit from the water transfer [69].

The SNWDP has coordinated and balanced many relationships, such as those between humans and nature and economic development and ecological protection during its construction. Through water quality protection and ecological compensation and restoration, it not only meets the survival and development needs of the current generation but also brings benefits to future generations. It enables people of different generations to benefit from the fruits of "shared development" [70].

The project has social impacts, including displacement of local communities and cultural heritage loss. Communities have been relocated to make way for the project, and their traditional livelihoods and cultural practices have been destroyed or disrupted. Huge negative social impacts stem from the eviction of 375,000 people to enlarge the Danjiangkou reservoir and construction of related canals [41]. In total, 10 million people have historically been moved due to the construction of the reservoir [64]. This must be weighed against better water and food security for the at-present 150 million people in northern China benefitting from the SNWDP. Negative social effects also stem from the fact that waterborne diseases and pollutants risk being transported through the project from south to north. Specifically, schistosomiasis-infected snails can transfer from the south and infect people in the north [71,72]. Adding to this, other types of pollutants typical of the south such as heavy metals, microbes and viruses, saline water, and emerging pollutants will affect the social sustainability of the project [73–75].

These concerns are typical of large transboundary water transfer projects [6–8,76], especially where agricultural water use efficiency is low [77–79]. Thus, it is important that water transfer is accompanied by optimal demand management and water quality and quantity conservation based on Integrated Water Resources Management (IWRM) and UN Sustainable Development Goals (SDGs) [26]. This includes establishing regional water recycling systems, promoting water-saving technologies in industry and agriculture, and reducing the area of high-water-consuming crops [80,81].

3.2. Global Aspects of SNWDP

The South-to-North Water Diversion Project (SNWDP) is not only a transformative domestic infrastructure but also a project with significant global implications. Its scale, ambition, and outcomes reverberate beyond China's borders, influencing international food security, climate resilience, hydropolitics, and global governance debates.

China's future water needs are shaped by climate change and population trends. By 2050, after the SNWDP is completed, China's population is projected to decrease by about 100 million, possibly falling below 800 million by 2100 according to UN demographic models [82]. Studies on climate change effects on crop growth in China are mixed: some show positive impacts [83], while others—excluding CO_2 fertilization—show negative effects [84,85]. Global climate models for precipitation remain uncertain [86], but most do not predict major changes for China, with some suggesting a 5–7% increase in mean annual precipitation by 2050 [87].

Despite a shrinking population, ensuring food and water security remains a challenge. China imports about a quarter of its food, and its domestic production and self-sufficiency policies significantly influence global food markets [88,89], especially during concurrent droughts. The risk of simultaneous droughts in major grain-producing countries has risen due to climate change and is expected to increase further. Such events, combined with conflicts like the Ukraine–Russia war, intensify global food security concerns. China's self-sufficiency policy and the SNWDP are likely to help mitigate future international food crises.

The lack of major changes in precipitation, potential positive effects on crop growth, a declining population, and improved water management via the SNWDP all support the prospect of reduced food insecurity in China. Zhan [90] highlights China's transformation over the past 50 years from struggling to feed itself to becoming a major global food actor, though it still relies heavily on imports. China also invests in overseas agriculture, with about 300 million tons of cereals traded globally—roughly 50% of China's annual needs. Domestic droughts can thus have serious global price impacts, making the SNWDP a crucial measure for improving self-reliance.

Long et al. [65] note that ongoing water diversions are essential for sustainable water management. China is developing a national water grid for coordinated monitoring and control of water and energy flows at the national scale [91]. For long-term water quality, recent studies on the east route show improved ecological conditions during water transfer periods, with Dongping Lake shifting from eutrophic to mesotrophic status.

A recent study on the middle route of the SNWDP concluded that several meteorological parameters, including precipitable water vapor (PWV), precipitation, and three types of soil moisture, have shown significant improvements with high statistical confidence, indicating positive regional restoration [92]. Another recent study, taking SNWDP as a special case of inter-basin water transfer (IBWT), used a comprehensive benefit assessment framework approach to estimate multi-regional benefits including investment benefits, water resource benefits, ecological benefits, and opportunity development cost losses for the eastern and middle routes of the SNWDP [93]. The main focuses were on the ecological and economic benefits. For the economic benefits, they found the net benefits of the SNWDP amounted to USD 207 billion; when compared during the operational phase (2014–2020), the benefits amounted to USD 18.4 billion, with water resource benefits as the dominant benefit. This means that the operational benefit was only 9% of the net benefit for the same period. For the ecological benefit, it was evaluated based only on land-use type changes and the ecosystem service value coefficient, without mentioning environmental aspects, such as environmental flow, although groundwater benefits included the prevention of groundwater funnel decline and ground subsidence, regulation and storage benefits, and energy-saving benefits. However, it is very valuable that the study used a comprehensive framework to include parameters such as investment benefits; water resource benefits; and opportunity losses in development, as well as ecological benefits to calculate the total and net benefits of SNWDP.

There are, however, more extensive and often interlinked global aspects of the SNWDP. The project is a colossal engineering and political undertaking whose scale, social costs, and knock-on effects have global consequences, e.g., [31,44]. Zhao et al. [94] found that the middle route of the SNWDP led to a consistent increase in both total water supply and agricultural water consumption in the region from 2010 to 2020. It significantly boosted grain production and thus offers actionable insights to improve global water management and agricultural sustainability. This boost in agriculture leads to economic and social development; however, it continuously increases the water demand in the receiving region, with implications such as social costs (large resettlement and local economic disruptions) [14,26]. These trade-offs are relevant globally for cost–benefit frameworks used when planning large water infrastructure.

Even though the SNWDP does not include international transboundary rivers, large water projects like this raise international concerns and send geopolitical and transboundary ripple effects to neighboring transboundary downstream countries (notably India). This can shift regional diplomacy over water security, e.g., [42,95]. This, together with China's increasing economic power, have implications for technology transfer, norms, and "exportable" governance models. China's know-how in engineering, tunneling and pumping tech, project financing, and institutional arrangements is gradually becoming a part of the global toolbox (and an exportable model) for other countries involved in large water projects, e.g., BRI-linked hydraulic projects. At the same time, the SNWDP raises questions about sustainability standards, environmental safeguards, and stakeholder participation that global development agencies and governments must weigh when adopting similar approaches [31,44].

Recent studies have also quantified the SNWDP's effects on China's water balance and agricultural output. Zhao et al. [94] used the Synthetic Control Method to show that the middle route led to a consistent increase in both total water supply and agricultural water consumption in Henan Province from 2010 to 2020, significantly boosting grain production and stabilizing yields, especially after 2017 [94]. Yang et al. [93] assessed meteorological changes in the middle route area, showing SNWDP reversed declining trends post-2014 [93]. Chang et al. [96] used satellite data to show increased surface water storage and improved water quality in SNWDP-affected areas [96]. Cheng et al. (2023) quantitatively evaluated SNWDP's impact on water use efficiency, showing constant improvement in affected regions [97]. These analyses used a comparative impacts approach to water balance and agricultural yields in a positive way, but without much concern about irrigation efficiency in particular and water use efficiency in general.

National and regional projections suggest that, if advanced water-saving technologies are adopted at scale, annual water savings in the North China Plain alone could reach 8–10 km^3 by 2030 [77–79]. This would not only enhance the redundancy and resilience of the SNWDP but also reduce pressure on donor basins and improve overall water allocation efficiency. Policy instruments such as water rights trading, tiered water pricing, and incentives for water-saving crops are being piloted to further encourage efficient water use [80,81].

Climate modeling studies further indicate that the SNWDP has led to increased precipitation and reduced temperatures in water-receiving areas, with annual precipitation rising by 2.8 mm and spring temperatures dropping by 0.15 °C, effects that can buffer agricultural systems against climate variability [92,96]. Such hydrological interventions can help reduce the risk of crop failures during extreme weather events, supporting both national and global food security objectives [83].

3.3. Population, Irrigation Efficiency, and Food Self-Sufficiency

China's policy of food production self-sufficiency, supported by the SNWDP, has direct and indirect effects on international grain markets. As highlighted by Zhan (2022), China's influence on global food prices is substantial, especially during concurrent droughts in major grain-producing countries [90]. Murphy et al. (2024) show that interventions improving water availability and irrigation efficiency are among the most cost-effective for enhancing food security and climate resilience globally [98]. Akchaya et al. (2025) show that intercropping of legumes is beneficial for resource use efficiency, food security, and thus, climate resilience, with implications for SNWDP-supported agriculture [99]. Kabato et al. (2025) evaluate climate-smart agriculture strategies for food security and resilience, emphasizing irrigation and nutrient management [100]. Yang et al. (2023) examine sustainable irrigation and climate feedback, showing irrigation's role in boosting yields and climate adaptation [101]. De Pinto et al. (2023) explore resilience integration in food security research and practices, with lessons for the SNWDP's climate adaptation role [102]. The SNWDP's climate adaptation in relation to food security and IWRM should be lifted to a higher level by decision makers to tackle the integrated impacts.

Irrigation efficiency is a critical factor in the SNWDP's impact. Studies show that water transfer projects like the SNWDP can significantly improve irrigation water use efficiency, especially in arid and semi-arid regions [77–79,103]. By providing reliable water supplies, the SNWDP enables the adoption of advanced irrigation technologies, such as drip and sprinkler systems, which reduce water losses and increase crop yields [67]. Ma & Wang (2024) found that the SNWDP promoted water use efficiency in the Yellow River Basin, leading to more sustainable agricultural practices [67]. These improvements not only boost domestic food production but also reduce China's reliance on global grain imports, helping to stabilize international food prices [88]. However, high water tariffs and water use efficiency in all user sectors remain challenges in terms of future societal sustainability. While the SNWDP primarily addresses water scarcity through large-scale supply-side interventions, demand-side management is increasingly recognized as essential for sustainable water resources in China. Recent policy and research emphasize the adoption of advanced irrigation technologies, such as drip, sprinkler, and precision irrigation systems, which can significantly reduce agricultural water demand. Studies indicate that the widespread implementation of these technologies in northern China could achieve water savings of 30–50% compared to traditional surface irrigation methods [67,77–79]. For example, Ma & Wang (2024) found that the SNWDP promoted water use efficiency in the Yellow River Basin, with modern irrigation practices contributing to more sustainable agricultural production [67]. This means that integrating demand-side measures with supply-side infrastructure is critical for maximizing the benefits of the SNWDP. Continued investment in water-saving technologies, farmer education, and institutional reforms will be necessary to achieve long-term water security and sustainability in China's arid and semi-arid regions.

To assess the long-term implications of the SNWDP on China's food security and global markets, Figure X presents projected trends for China's population, irrigation water use efficiency, and food self-sufficiency from 2020 to 2100. According to United Nations demographic models, China's population is expected to decline from approximately 1.4 billion in 2020 to below 900 million by 2100 [82]. Concurrently, irrigation water use efficiency is projected to increase from about 50% in 2020 to 80% by 2050, driven by the adoption of advanced technologies such as drip and sprinkler systems [67,77–79]. Food self-sufficiency is expected to rise from 70% to 85% by mid-century, reducing reliance on imports and stabilizing global grain markets during periods of concurrent droughts [90].

These trends indicate that improved water management through SNWDP, combined with demand-side measures, will significantly enhance China's resilience to climate variability and global food supply shocks. The integration of supply-side infrastructure with efficiency improvements is critical for achieving sustainable water and food security goals. Projected trends for population, irrigation efficiency, and food self-sufficiency from 2020 to 2100 are presented in Figure 2. Populations projections are based on data published by the United Nations for population projections [82]; irrigation efficiency projections are based on Ma & Wang (2024) and related studies [67,77–79]; food self-sufficiency projections are adapted from Zhan (2022) [90].

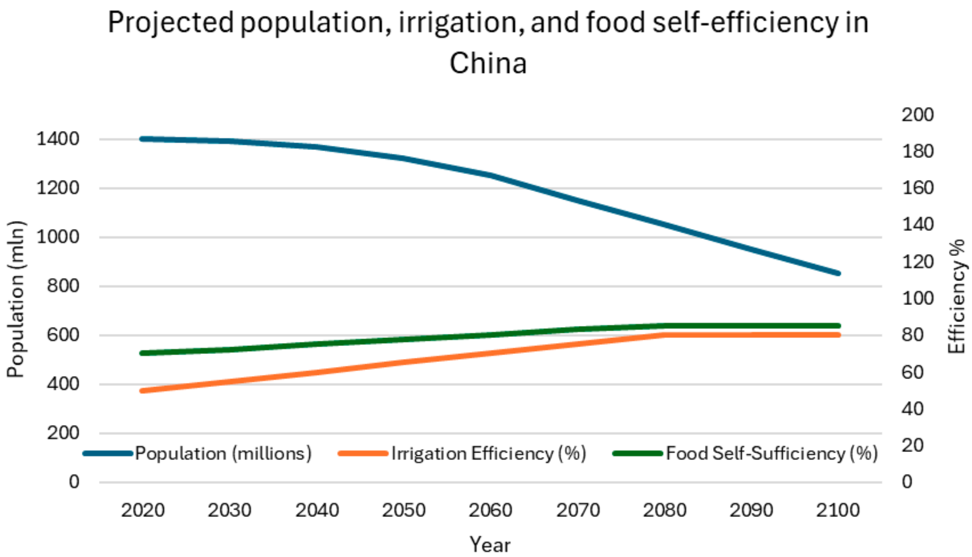

Figure 2. Projected trends for China's population (millions, blue), irrigation water use efficiency (%; green), and food self-sufficiency (%; orange) from 2020 to 2100 in China.

4. Hydropolitical and Geopolitical Attributes and Debate of the SNWDP

Although the SNWDP does not directly involve international transboundary rivers, its scale and precedent raise concerns among neighboring countries, particularly regarding future extensions such as the Red Flag River project [41,42]. The Belt and Road Initiative (BRI) amplifies these transboundary effects, as China's water engineering expertise and governance models are increasingly being exported to other countries [46,103]. BRI-related infrastructure projects have been shown to facilitate technology transfer, talent development, and industrial upgrading, but also pose environmental and geopolitical risks [46,104–107]. Green technology spillovers from China's outward investment under BRI are significant, especially in middle- and low-income countries with high institutional quality [46]. In addition, the SNWDP serves as a test case for water governance models. Webber (2017), Moore (2014), and Lin (2017) provide differing interpretations of the project's governance and environmental implications [13,34,35,41]. Dai et al. (2025) review smart water management, governance innovation, and technological integration in China, including SNWDP pilot programs [107]. Bilalova et al. (2024) systematically review water governance paradigms, showing participatory and integrated approaches yield better sustainability outcomes [108]. Daniell (2012) provides international case studies on co-engineering and participatory water management [109]. Alvarado-Arias et al. (2025) show participatory river governance through citizen science improves outcomes over technocratic models [110]. Ali & Kamraju (2024) review community participation in sustainable integrated water resource management [111]. Its outcomes inform global debates on whether large inter-basin transfers are a viable long-term adaptation to water scarcity under climate change, how to weigh social and environmental costs against development gains, and how upstream infrastructure can reframe regional diplomacy [44,112]. Chinese authorities and decision makers have a profound interest in technocratic and megaprojects in seeking solutions for strategic hydrological and environmental problems. Despite the lack of transparency throughout the decision-making, planning, and implementation processes, the hydropolitical and geopolitical attributes and debate can never be neglected. Lin [41] concluded that the SNWDP is not merely a technical solution but a political instrument. It prioritizes capital-intensive engineering over governance reforms and demand-side management with reflection of a state-driven ideology rooted in Maoist beliefs that humans can conquer nature, an ethos that still influences infrastructure decisions today. The same author also pointed out that the common understanding of the SNWDP can be compared to historical and global water diversion efforts (e.g., Grand Canal, California Water Project), arguing that such interventions are commonplace and strategically justified. Moore [35] discussed two theoretical frameworks as the backbone of the SNWDP: ecological modernization (environmental reform through technological innovation and institutional change) as well as authoritarian environmentalism (authoritarian regimes can implement environmental policies through technocratic and top-down approaches). A potential advantage would be the reflection of the state's ability to co-opt environmental concerns to serve broader strategic goals, such as (a) economic development in water-scarce northern regions; (b) political control and regime legitimacy, and (c) social stability through resettlement and compensation [34,35,113,114].

In a major project at the University of Melbourne, Webber [24] and colleagues presented in-depth, interdisciplinary, and technopolitical aspects of the SNWDP in a series of papers, emphasizing the socio-political, hydrological, and economic dimensions of the project, and concluded that, in terms of policy implications, among other aspects such as governance complexity, local misalignment and environmental and energy trade-offs, the project tests the limits of centralized governance and offers lessons for managing large-scale inter-basin water transfer schemes globally (see further) [25,39,115–123]. On the other hand, Moore found a problem with the centralized governance structure related to its lack of formal inter-jurisdictional dispute resolution mechanisms. He argued that while vertical control limits central–local divergence, it fails to address horizontal conflicts among provinces, which often pursue localized interests at the expense of neighboring jurisdictions [35]. Both the above authors converge on the insight that effective water governance requires more than infrastructure: they advocate for interdisciplinary integration of hydrological and social sciences to understand systemic and local interactions and they call for institutional innovation to resolve horizontal conflicts and collective action problems. This aligns with IWRM principles and SDG 6 (Clean Water and Sanitation).

The SNWDP can probably be best understood as a state-building and growth-stabilization project as much as a water project. It has delivered tangible security dividends to northern metros and signaled formidable state capacity. Yet it entrenches a supply-side, techno-fix pathway that redistributes risk southward, narrows participatory politics, and may underperform under climate volatility. A more resilient trajectory would flip the hierarchy: demand-side efficiency and institutional reform first; targeted transfers second; and any western high-plateau diversions last, if at all, and only with robust ecological safeguards, transparent accounting, and meaningful representation for affected communities.

In a comparative perspective aspect, the SNWDP stands among the world's largest water transfer megaprojects, comparable in scale and ambition to projects such as the California State Water Project (SWP), India's Indira Gandhi Canal, the Central Arizona Project (CAP), the Aswan High Dam, the Three Gorges Dam, and the Grand Ethiopian Renaissance Dam (Millennium Dam). Table 2 presents the key metrics of these projects. Huang et al. (2024) find the SNWDP leads to an 8.2% increase in grain output and 4.7% boost in agricultural productivity compared to other water transfer projects [123]. Yang et al. (2024) provide a multi-regional benefit assessment of the SNWDP, showing USD 207 billion in comprehensive benefits, with lessons for other IBWT projects [93]. Feng et al. (2024) assess ecological risks in SNWDP and other world-class water transfer projects [124]. Zhou et al. (2024) propose joint optimal operation strategies for water supply equity and efficiency, which are relevant for comparative analysis [125]. These comparisons and lessons provide a collective cornerstone for the complex challenges implied by many IBWT projects worldwide.

Overall, however, SNWDP can be further scrutinized through three lenses, namely (1) political ecology and environmental justice, e.g., [126], (2) state spatial strategy and the "hydraulic mission", and (3) technopolitics and authoritarian environmentalism. From a political ecology and environmental justice perspective, the SNWDP redistributes hydrological risk and benefit across social class and regional lines, moving water (and ecological costs) from the relatively poorer, rural "source" regions to powerful urban-industrial cores (Beijing–Tianjin–Hebei; the so-called Jing–Jin–Ji), with limited avenues for contestation. Looking at state spatial strategy and the "hydraulic mission", the project extends a century-long Chinese (and global) tradition of nation-building through mega-hydraulic structures. Water transfer serves as a material instrument for knitting together key urban corridors (the Jing–Jin–Ji), thus stabilizing accumulation in the North China Plain, and projecting state capacity. Using technopolitics and authoritarian environmentalism, the state mobilizes engineering expertise, securitized framing (water security), and cadre evaluation to legitimate exceptional interventions (long canals, strict protection zones, and mass resettlement). Participation is circumscribed; legitimacy flows from performance claims, drought proofing, air-quality co-benefits (via reduced coal washing), and groundwater recovery, more than from procedural inclusion. Given the scale and strategic importance of the SNWDP, the security and robustness of its infrastructure are critical considerations and should be added as the fourth lens. The SNWDP incorporates advanced engineering standards for seismic safety, flood control, and operational redundancy, as mandated by national regulations and detailed in recent technical assessments [32,33,44]. Regular safety inspections, real-time monitoring systems, and emergency response protocols are implemented to ensure the reliability of the canal network and associated facilities [33].

Risk analyses have evaluated the potential consequences of malfunctions or failures, such as canal breaches, pump station breakdowns, or major flooding events. These studies indicate that while the probability of catastrophic failure is low due to robust design and maintenance, the consequences could be severe, including large-scale water supply disruptions, economic losses, and environmental damage. As a result, contingency planning and rapid response mechanisms are integral to project management.

Regarding intentional attacks or sabotage, public literature on the SNWDP is very limited, likely due to the sensitive nature of such assessments. However, the project is classified as critical national infrastructure, and security measures—including surveillance, restricted access, and coordination with public security agencies—are in place to mitigate risks [40]. The potential impacts of intentional attacks have been considered in national water security strategies, emphasizing the need for ongoing vigilance and adaptive risk management.

Table 2. Comparison of key metrics for major water transfer/irrigation projects.

Project	Country	Completion Year	Annual Water Transfer (km^3)	Length (km)	Main Purpose	Irrigation Efficiency Impact	Social Impact (Resettlement)	Major Environmental Issues	Reference Numbers
SNWDP	China	2050 (planned)	~45	~4350	Urban and Agriculture	Significant improvement [67,77–79]	~375,000 direct; 10 million historical [12,62]	Salinity, ecosystem change, disease transfer [6,22,57–59,71–79]	[3,5,6,12,22,38,57–60,65,67,71–79]
California SWP	USA	1973	~4.4	~1100	Urban and Agriculture	Moderate improvement [12]	Thousands	Groundwater depletion, habitat loss [12]	[3,5,6,12]
Central Arizona Project (CAP)	USA	1993	~1.85	~541	Urban and Agriculture	Moderate [12]	Limited	Salinization, water table decline [46]	[3,5,6,12]
Indira Gandhi Canal	India	2010	~5.5	~650	Agriculture	Moderate [5,12]	Tens of thousands	Waterlogging, salinization [5,46]	[3,5,6,12]
Aswan High Dam	Egypt	1970	~55 (reservoir capacity)	N/A	Agriculture and Power	Moderate [41]	>100,000	Salinity, ecosystem change [6,46]	[3,5,6,12]
Three Gorges Dam	China	2012	~39 (reservoir capacity)	N/A	Power and Flood Control	Limited	>1.3 million	Sediment, ecosystem change [6,46]	[3,5,6,12]
Grand Ethiopian Renaissance Dam (Millennium Dam)	Ethiopia/ Sudan	2023	~74 (reservoir capacity)	~1800	Power and Irrigation	Potential for major improvement [31]	Limited direct, but regional impacts [31,32]	Downstream flow changes, regional hydropolitics, ecosystem change [30–32]	[30–32]

The supply management of water risks increases water-intensive growth in the north, while conveying water scarcity to the south [127]. This stabilizes investment and real estate expansion in dry northern metros but can aggravate southern basin stress in dry years, especially as climate variability increases. Strong dependence on inflow from the Yellow River could become a systemic risk if multiyear droughts, heatwaves, or upstream development tighten supply. However, locating water-intensive production in water-secure regions, scaling water-rights trading beyond pilots, and shifting cropping patterns can reduce North China Plain dependence, e.g., [128,129]. Recent studies have shown that the SNWDP has had positive economic impacts on the areas affected by the project. For example, some recent studies on the central route of the SNWDP indicate that water use efficiency is constantly improving along this project stretch [115]; and the economic status of the areas that receive water has increased relative to other regions [130]. The main reason for this increased economic development level is that water diversion encourages growth of the service industry in the water-receiving areas by supplying water for domestic use. Additionally, the SNWDP has promoted the growth of large-size enterprises in the water-receiving areas [131]. The middle route of the SNWDP has benefited Henan, Hebei, Tianjin, and Beijing since 2014 with sustainable changes to the cities, groundwater, ecological environment, industrial structure, and social development of the beneficiary areas [131].

5. Conclusions

The South-to-North Water Diversion Project (SNWDP) stands as one of the world's most ambitious water transfer megaprojects, with profound implications for China and the international community. This review, drawing on the latest literature and data, underscores that the SNWDP is not merely a domestic hydraulic intervention but a transformative force with global economic, environmental, and geopolitical dimensions.

From a domestic perspective, the SNWDP has already delivered substantial benefits in alleviating water scarcity in northern China, stabilizing groundwater levels, and supporting agricultural productivity and urban development. The operational eastern and central routes have contributed to improved water security for over 150 million people, reduced flood risks in the Yangtze River Basin, and fostered socioeconomic growth in recipient regions. However, these gains are counterbalanced by significant challenges, including complex and escalating project costs, large-scale resettlement and social disruption, and persistent environmental risks such as ecosystem alteration, salinity intrusion, and pollutant transfer. The ongoing need for robust mitigation measures and transparent evaluation remains critical for the project's long-term sustainability.

Internationally, the SNWDP's influence extends far beyond China's borders. By enhancing China's food production self-sufficiency, the project has the potential to stabilize global food markets, especially during periods of concurrent droughts in major grain-producing regions. The SNWDP also serves as a model for large-scale water management, technology transfer, and governance innovation, with lessons, both positive and cautionary, for other countries pursuing similar infrastructure under the Belt and Road Initiative. At the same time, the project raises important questions about transboundary water governance, environmental justice, and the exportability of China's technocratic approach to water management.

The future trajectory of the SNWDP, particularly the planned western route, will be pivotal. This phase may involve the "water tower of Asia," with possible transboundary implications for neighboring countries and regional hydropolitics. As such, continuous monitoring, international dialogue, and adaptive management are essential to ensure that the project's benefits are maximized while minimizing adverse impacts.

In conclusion, the SNWDP exemplifies the opportunities and dilemmas of mega water transfer projects in the 21st century. Its evolving legacy will depend on the ability of policymakers, engineers, and stakeholders to balance economic development, environmental stewardship, social equity, and international cooperation. Ongoing research, transparent data sharing, and participatory governance will be vital to realizing the project's promise for both China and the global community.

Based on the above discussion, the following key points can be highlighted as the main characteristics:

Domestic Water Security and Socioeconomic Benefits: (1) The SNWDP has significantly alleviated water scarcity in northern China, stabilized groundwater levels, and supported agricultural and urban development, benefiting over 150 million people. (2) The project has contributed to socioeconomic growth in recipient regions and reduced flood risks in the Yangtze River Basin.

Economic and Environmental Trade-Offs: While the SNWDP has delivered substantial economic benefits, the true costs remain difficult to assess due to complex project financing, resettlement, and ongoing mitigation measures, and environmental challenges, including ecosystem alteration, salinity intrusion, pollutant transfer, and the need for continuous ecological compensation and restoration.

Social Impacts and Equity: The project has caused large-scale resettlement and social disruption, with up to 375,000 people directly relocated and broader impacts on local communities and cultural heritage. Social sustainability requires ongoing attention to water-borne disease risks, pollutant transfer, and equitable benefit distribution.

Global and Geopolitical Implications: The SNWDP enhances China's food production self-sufficiency, which can help stabilize global food markets, especially during concurrent droughts in major grain-producing regions.

It is claimed that the project serves as a model for large-scale water management, technology transfer, and governance innovation but also raises questions about transboundary water governance and environmental justice. The planned western route of the SNWDP may involve the "water tower of Asia," with potential transboundary implications for neighboring countries and regional hydropolitics. Continuous monitoring, transparent evaluation, international dialog, and adaptive management are essential to maximize benefits and minimize adverse impacts.

The SNWDP exemplifies the opportunities and dilemmas of mega water transfer projects in the 21st century. Its legacy will depend on balancing economic development, environmental stewardship, social equity, and international cooperation. Ongoing research, transparent data sharing, and participatory governance are vital for ensuring the project's long-term sustainability and for informing similar initiatives globally.

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