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A Review of the Eco-Environmental Impacts of the South-to-North Water Diversion: Implications for Interbasin Water Transfers

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ABSTRACT

Interbasin water-transfer schemes provide an engineering solution for reconciling the conflict between water demand and availability. In the context of climate change, which brings great uncertainties to water resource distribution, interbasin water transfer plays an increasingly important role in the global water–food–energy nexus. However, the transfer of water resources simultaneously changes the hydrological regime and the characteristics of local water bodies, affecting biotic communities accordingly. Compared with high economic and technical inputs water-transfer projects require, the environmental and ecological implications of water-transfer schemes have been inadequately addressed. This work selects the largest water-transfer project in China, the South-to-North Water Diversion (SNWD) Project, to critically review its eco-environmental impacts on donor and recipient basins, as well as on regions along the diversion route. The two operated routes of the SNWD Project represent two typical water diversion approaches: The Middle Route uses an excavated canal, while the East Route connects existent river channels. An overview of the eco-environmental implications of these two routes is valuable for the design and optimization of future water-transfer megaprojects.

1. Introduction

Climate change brings increasing uncertainty to global water security and aggravates the uneven distribution of water resources [1,2]. Interbasin water transfer provides an engineering solution for relieving the contradiction between water demand and supply, especially in large countries with intense spatial and temporal variations in water resource distribution [3]. For example, from 1985 to 2017, the United States newly established 1905 interbasin water-transfer projects [4], and China transferred more than 1×10^{11} m^3 of water through 16 000 km of canals by 2015 [5]. The improvement of engineering techniques is further increasing the feasibility of water-diversion projects as an option for sustaining the water–food–energy nexus; interbasin water-transfer schemes are expected to account for around 25% of global water withdrawals by 2025 [6,7].

Interbasin water transfer is defined as "the transfer of water from one geographically distinct river catchment or basin to another, or from one river reach to another," which theoretically includes intrabasin transfers as well [8,9], hence resulting in the concepts of "donor" and "recipient" basins or rivers. Although the redistribution networks based on water-transfer schemes have satisfied the needs of anthropic production, such large-scale projects have a disturbing potential to cause severe perturbation to the ecosystems of the donating and receiving basins, as well as to the diversion route areas. A change in water quantity in space triggers variations in the hydrological regime and water quality, which result in complex, hysteretic, and comprehensive impacts on the aquatic environment and ecosystem [10]. On the one hand, the introduction of water into the receiving basin may restore a previously damaged ecological system [11,12] and improve water quality, due to enhanced water exchange [13]. On the other hand, established interbasin water-transfer schemes worldwide have reported a series of environmental and ecological issues. Water transfers from the Lower River Murray in south Australia caused the water quality of the receiving water to deteriorate by

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increasing the turbidity and salinity, resulting in a rising cost of water treatment [8,14]. The São Francisco River Integration Project in Brazil accelerated algae growth in part of the receiving reservoirs and increased algal bloom risks [15]. The Orange River Project in South Africa considerably altered the composition of benthic macroinvertebrate communities in the receiving river, because the water transfer changed the previously seasonal river into a perennial river [16]. Furthermore, habitat alteration and the spread of aquatic invasive species are the common ecological consequences of interbasin water transfers [17–19].

The South-to-North Water Diversion (SNWD) Project is the world's largest interbasin water-transfer scheme. In addition to the environmental and ecological effects mentioned above, the SNWD Project has encountered unexpected challenges that provide valuable experience for future water-diversion projects—particularly those in the proposal and design stages. This study critically reviews the positive and negative eco-environmental impacts of the SNWD Project on local freshwater systems and draws key messages from this analysis to provide comprehensive and forward-looking insights into the eco-environmental implications of interbasin water transfer.

2. The SNWD

The SNWD Project was launched by the Chinese government in 2002 to mitigate water scarcity in the arid north and northwest regions. For example, Beijing and Tianjin have the lowest per capita volume of water resources and per capita water use among the presented regions (Fig. 1), which means that these cities face high water-shortage stress. However, there has been limited room for water utilization efficiency improvement. The SNWD Project includes three transfer lines: the East Route, Middle Route, and West Route [20]. According to the project plan, the SNWD Project will divert 4.48×10^{10} m^3 of water per year from the Yangtze River Basin to north and northwest China by 2050, with the planned West Route accounting for the greatest water-transfer quantity (Table S1 in Appendix A) [21,22]. After its implementation, the SNWD Project will connect the Yangtze, Huaihe, Yellow, and Haihe rivers, which are the nation's four major rivers, and will play a key role in the national water supply system.

The East Route draws water from the lower reach (Sanjiangying in the Yangzhou section) of the Yangtze River and supplies water for Tianjin and the Jiaodong Peninsula of Shandong Province, mainly through the existing river channels of the Beijing–Hangzhou Grand Canal (green line in Fig. 1). The first phase of the East Route is 1466 km long and connects a chain of large lakes, including the Hongze, Luoma, Nansi, and Dongping Lakes. There are 13 levels of pumping stations in the route to gradually introduce water from the Yangtze River to Dongping Lake. The Middle Route diverts water from the expanded Danjiangkou Reservoir in Hubei Province to Beijing and Tianjin through a newly excavated canal (red line in Fig. 1). The Middle Route is 1432 km long in total and consists of a 1196 km open canal and a 236 km culvert [13]. It is fully concreted, with a trapezoidal cross-section to prevent pollutant input and maintain the high quality of water from the reservoir. Moreover, effective seepage-control measures, including continuous full-face concreting, were employed to maintain a dry dyke, thereby ensuring that there is no groundwater inflow to the canal. An isolation zone (15 m wide) was established on both sides of the canal to prevent runoff pollution. In addition to the main project of the water-diversion work, a series of auxiliary projects have been simultaneously carried out the East and Middle Routes, such as water pollution control, water and soil conservation, lake and wetlands restoration, and so forth, to ensure the quality of the diverted water (Table S1). The West Route is currently at the proposal stage; its planned location is the Qinghai–Xizang Plateau, which is mostly covered by permafrost and has harsh weather conditions [23]. The purpose of this route is to supply water to areas experiencing water shortages in the upper reach of the Yellow River Basin, such as Qinghai, Gansu, and Ningxia. According to the plan, the West Route will be constructed in three stages and will be able to transfer 1.7×10^{10} m^3 of water per year after completion [24]. To achieve this goal, the West Route will include the construction of canals, tunnels, and high dams. The vulnerability of the local environment and the complexity of the required engineering increase the difficulty of the establishment of the West Route, leading to widespread discussion among policymakers and scholars.

3. Eco-environmental impacts of the SNWD

The eco-environmental impacts of an interbasin water-transfer scheme cover impacts to the donor basin, transfer line, and recipient basin and involve a broad range of effects. A schematization of these major eco-environmental impacts is illustrated in Fig. 2.

3.1. Impacts on the donor region

3.1.1. The Middle Route

Water withdrawals from the donor basin may decrease the discharge and sediment transportation in downstream rivers [25]. The

Fig. 1. Sketch map of the Middle and East Routes of the SNWD Project. The background figures used the site photos of the Middle Route (left) and East Route (right). The total volume of water sources (blue bar), total volume of water consumption (yellow bar), per capita volume of water resources (orange bar), and per capita water use (turquoise bar) for each province and city were calculated based on data from the *China Water Resources Bulletin 2020* and *Chinese Census 2020*.

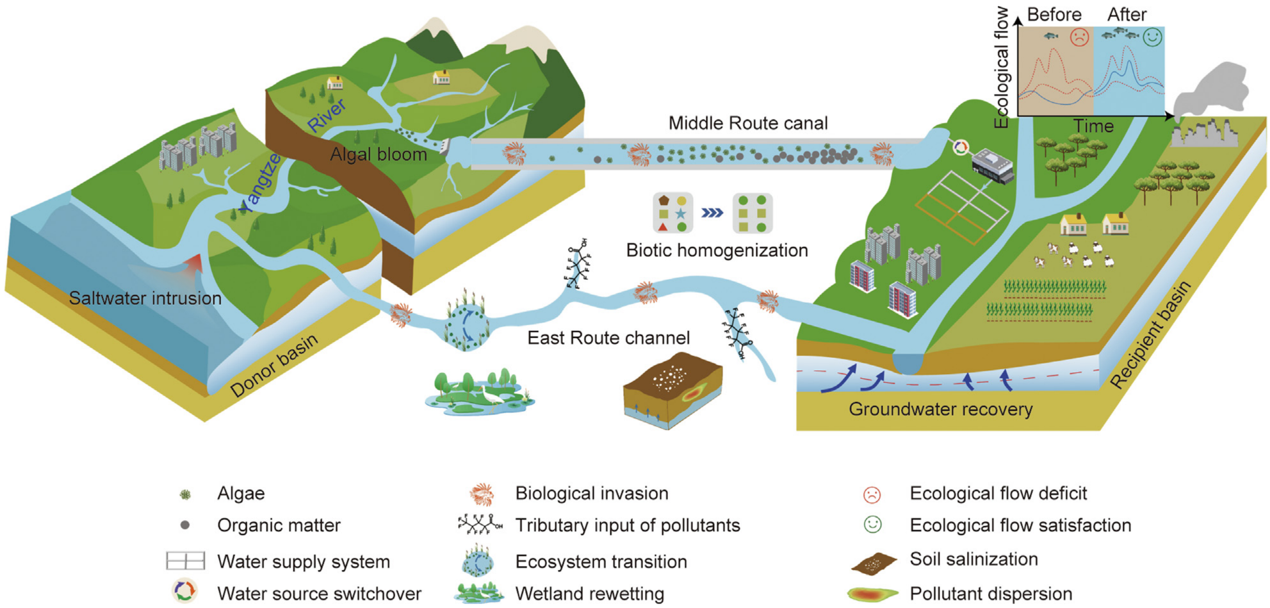

Fig. 2. Schematic summary of the major eco-environmental impacts of the Middle Route (concrete canal) and the East Route (connection of existing river channel) of the SNWD on the donor basin (left), water-transfer lines (middle), and recipient basins (right). The annotation of the symbols is listed at the bottom of the figure. *Ecosystem transition* refers to the transition from one type of ecosystem to another due to significant changes in the structure, function, and/or composition of an ecosystem. *Wetland rewetting* refers to the process of restoring a degraded or drained wetland by recovering its natural hydrological conditions. *Soil salinization* refers to the accumulation of salt in the soil due to an increasing groundwater level. *Pollutant dispersion* refers to the transport of pollutants due to enhanced groundwater flow.

Middle Route is a typical case that has reduced the outflow discharge of the Danjiangkou Reservoir to the mid-downstream of the Hanjiang River (Table S2 in Appendix A), a large tributary of the Yangtze River. There are also a series of cascade reservoirs in the Hanjiang River (Table S3 in Appendix A), as well as other water-transfer schemes such as the Yangtze–Hanjiang Water-Diversion Project, which serves as an auxiliary project of the Middle Route. Compared with dams, water transfers play a relatively minor role in altering the hydrological regime of a river (Table S4 in Appendix A). However, the operation of the Middle Route is having profound effects on the freshwater ecosystem in the middle and lower reaches of the Hanjiang River. Table 1 [26–34] summarizes and compares the major indexes reflecting the water and fish habitat qualities in the affected reaches of the Hanjiang River before and after the water diversion, and detailed explanations are presented in Section S1 and Table S5 in Appendix A. The results show decreasing discharge and the continuous input of pollutants from two-side regions with a high urbanization rate [35], which have caused the water quality to deteriorate (see pollution indexes in Table 1) [26] and increased the risk of algal blooms (see the algal bloom outbreak probability in Table 1 and Fig. 2) [27,36]. The integrated pollution index of water quality and single-factor pollution indexes based on the chemical oxygen demand (COD_{Mn}) and NH_3–N statistically increased after the water diversion of the Middle Route began (Fig. S1 in Appendix A). This is mainly attributed to the decreased aquatic environmental capacity and self-purification capacity of these reaches, due to the decrease in water flow [37,38]. Pollution has become more severe in wet seasons compared with dry seasons, probably owing to enhanced nonpoint source pollution in wet seasons [39,40]. Furthermore, the middle and lower reaches of the Hanjiang River have experienced large-scale harmful algal blooms four times since the operation of the Middle Route in 2015, 2016, 2018, and 2021, with an algal density higher than 1.0×10^7 cells·L^{-1} [41]. Diatoms, which are the dominant phytoplankton in the Middle Route, have remained as the dominant phytoplankton population in the four instances of algal blooms [42]. Ecological regulation provides a solution to control algal growth by eliminating suitable hydraulic conditions. For

Table 1
Comparison of aquatic environment quality before and after the SNWD Project.

Items	Before SNWD	After SNWD	References
Integrated pollution index of water quality*	0.37–0.55	0.50–2.64	[26]
Single-factor pollution index of the chemical oxygen demand (COD_{Mn})*	0.35–0.79	0.53–1.58	[26]
Single-factor pollution index of NH_3–N*	0.29–0.47	0.37–3.70	[26]
Algal bloom outbreak probability (%)[a]	7.41–8.64	12.35–13.58 (9.5×10^9 m^3) 17.28–18.52 (1.3×10^{10} m^3)	[27]
Number of spawning grounds of fish with pelagic eggs[b]	7 (1976); 7 (2004)	6 (2018)[c]	[28–30]
Number of species of pelagic fish	25 (1976); 21 (2009)	22 (2018) [c]	[28,30,31]
Fish biodiversity indexes			
Margalef richness index (*D*)	3.34 (1976); 4.89 (2004)	2.25 (2018)[c]	[32,33]
Shannon–Wiener diversity index (*H*′)	2.70 (1976); 2.74 (2004)	1.14 (2018)[c]	
Pielou evenness index (*J*′)	0.77 (1976); 0.72 (2004)	0.33 (2018)[c]	
Abundance of eggs and fry of four major carps (million)	471 (1976); 93 (2004); 32.45 (2007)	48.87 (2018)[c]	[28–30,34]

* Indicates statistically significant differences ($p < 0.05$) between two groups of data based on a Kruskal–Wallis test with a Dunn's test.
[a] The probabilities after SNWD were evaluated at different water-diversion capacities, which are annotated in the bracket.
[b] The year of data collection is annotated in the bracket after the data.
[c] Data was collected under the ecological regulation of cascade reservoirs.

example, Xin et al. [43] proposed a joint operation of the Danjiangkou Reservoir, Xinglong Reservoir, and Yangtze–Hanjiang Water-Diversion Project to ensure a flow rate of 1000 $m^3 \cdot s^{-1}$ at the Shayang Gauging Station and/or a flow rate of 800 $m^3 \cdot s^{-1}$ at the Xiantao Gauging Station for five days in order to prevent harmful algal blooms. However, they suggested that the recommended discharge rate was based on a simulation and that the efficacy of algal bloom control is uncertain, especially under climate change. The long-term solution is to cut down the input of phosphorus, which is considered to be the limiting nutrient for algal growth in the middle and lower Hanjiang River.

The operation of the Middle Route, together with cascade reservoirs in the Hanjiang River, has also significantly affected local fish reproduction and fish habitats. The middle and lower reaches of the Hanjiang River used to have a diverse array of fish species with high abundance, with commercial fish—particularly the four major Chinese carps—accounting for a dominant fraction [28]. Hydraulic engineering, including water transfers, altered the hydrological regime of the middle and downstream sections of the Hanjiang River, decreasing the biodiversity of fish and jeopardizing the spawning capacity of the four major Chinese carps, even in an ecologically regulated environment, as shown in Table 1. In contrast, the number of fish species that prefer still water and slow-moving water is showing an increasing trend [34]. One potential reason is that the weakening and even disappearance of peak flow has damaged the spawning activities of anadromous fish [44]. Meanwhile, the extension of the Danjiangkou Reservoir dam has changed the seasonal variation pattern of the water temperature, which has altered fish spawning periods and moved optimal spawning locations to more downstream sections [45]. In this case, an optimized and integrated reservoir operation strategy is greatly needed in order to achieve a balance among water supply, navigation, and ecological water demand.

3.1.2. The East Route

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. The estuary was previously vulnerable to salt intrusion, particularly in the north branch [46]. The implementation of the SNWD Project, including the East and Middle Routes, together with the Three Gorges Project, can aggravate the saltwater intrusion problem due to the decrease in the runoff of the Yangtze River and the lower water level at the estuary, especially during the dry season (Fig. 2) [47]. Although this influence is marginal compared with the effects of the Deep Water Channel Regulation Project and climate change, the joint effect of these hydraulic works could potentially aggregate the increase in tidally averaged surface salinity and thus affect the water withdrawal of the involved reservoirs during the spring and neap tides [48]. Su et al. [49] simulated the saltwater intrusion at the Yangtze River estuarine and found that the long-term water-diversion scheme of the SNWD Project at a discharge amount of 1600 $m^3 \cdot s^{-1}$ could lead to part of the estuarine area having a salinity greater than 1.5 and a largely extended unavailable water-intake time. Moreover, mega hydraulic engineering projects, including the SNWD Project, have reduced the riverine sediment in the Yangtze River and are predicted to slow down the progradation rate of tidal flats at the mouth area under the co-influence of sea level rise [50].

3.2. Impacts on water-transfer routes

3.2.1. The Middle Route

For the Middle Route, a highly protected water-conveyance canal has been established from the donor basin to the recipient basin; the canal is isolated from the local aquatic environment without interconnection to tributaries and has become an independent ecosystem. Hence, the Middle Route provides an excellent case to study how the source water and aquatic species evolve in such long-distance travel. Wang et al. [51] analyzed the quality patterns of the Middle Route water based on six years of monitoring data and reported that the temperature gradients between the southern and northern regions and the seasonal differences primarily drive the variations in pH and dissolved oxygen. Moreover, dry and wet deposition, together with runoff from bridges, can be overlooked pollutant sources. A total of 1750 hydraulic structures are located in the Middle Route; in particular, multiple bridges were newly built for this route, because the project construction intersected with the original road. Thus, pollutant discharge from traffic accidents is a potential pollution source for the Middle Route, which should be coped with in well-planned emergency measures [52]. Aside from external pollution sources, the microbial degradation of algal debris could be an important endogenous source of dissolved organic matter in the diverted water of the Middle Route channel [53].

Compared with the stability of the water quality, the ecosystem in the main channel of the Middle Route is developing at a juvenile stage with poor stability (Fig. 2). A simulation of the ecosystem via a mass-balance food web model suggested that the Middle Route system has a low utilization rate of primary productivity, which hinders the nutrients and carbon flowing into higher tropic levels and retards the energy flow in the system [54]. In line with these findings, Zhang et al. [55] found that the chlorophyll-*a* content and cell density of algae in the Middle Route gradually increased from the Danjiangkou Reservoir to the Beijing section. A microbial study also revealed that microeukaryotic populations acclimated better to the canal environment than bacterial communities, based on a local growth-factor comparison [56]. The two microbial groups adopt two different assembly patterns: Deterministic processes significantly affect the bacterial community, while the microeukaryotic community is dominated by stochastic processes.

Another major concern in using an open canal to divert water is the effect on animal migration and mortality, given that the open channel may act as an animal trap, causing the accidental death of surrounding animals or changing animal migration routes [8]. However, there are no related reports for the Middle Route, because it does not cross important ecological reserves and has strict protection measures to prevent the entrance of animals.

3.2.2. The East Route

Unlike the Middle Route, the East Route interconnects with local rivers and includes several impounded lakes as regulating reservoirs. Accordingly, the East Route has had more intricate and unpredictable impacts on local aquatic environments compared with the Middle Route. On the one hand, the East Route increases the hydraulic connectivity and concomitant water pollution-control measures by local governments and thus improves the water quality. Zhang et al. [57] analyzed the characteristics of the East Route water before and after the implementation of the SNWD Project and found that the water diversion obviously improved the water quality; in particular, the contents of nitrogen and organic pollutants were significantly decreased, which was attributed to pollution control and ecological restoration. The concentration of total nitrogen (TN) decreased by about 59% and COD decreased by about 16% after eight years of water diversion. Moreover, the water quality evaluated via an integrated index at all sampling sites during the water-transfer period was found to be significantly better than that for the non-water-diversion period within the same year. The water diversion also reduced the spatial variation in contaminant contents from upstream (south) to downstream (north) sections, where the downstream was previously more heavily polluted with nutrients than the upstream. Similarly, Qu et al. [58] used the water quality index (WQI) method to evaluate the water quality and spatiotemporal patterns of impounded lakes along the East Route and found a clear decreasing trend of nutrients, total suspended solids, and turbidity from the upstream to downstream lakes but an increasing tendency of chloride, conductivity, and total hardness. On the other hand, the East Route diverts water and simultaneously transports pollutants, including nutrients and emerging contaminants, which are mainly contributed by tributary input (Fig. 2). For example, Qu et al. [58] and Wan et al. [59] observed that water transfer caused the WQI scores of Hongze Lake to decrease compared with the scores in the non-water-transfer period, due to the accelerated diffusion of pollutants from hotspots to the entire lake. Zhuang et al. [60] analyzed the sources of trace metals in the sediments of Nansi Lake and found that suspended particle matter in the diverted water played an important role in accumulating trace metals in the lake sediments. Sun et al. [61] suggested that considerable amounts of polychlorinated biphenyls (PCBs) were transferred and deposited in the sediments of impounded lakes in the East Route, and that shipping probably enhanced the diffusion and release of PCBs from sediments.

From an ecological perspective, the water diversion supplements water for the rivers and lakes along the East Route, directly contributing to lakeshore wetland rewetting in affected regions [62]. The evolution of the Dongping Lake wetland landscape pattern shows that the water area and landscape-diversity index have gradually increased since the operation of the East Route [63], which has contributed to wetland rehabilitation and increased the ecological benefits of the SNWD [64]. However, an increase in water level in rivers triggers a rise in the groundwater table of two-side areas and may cause soil salinization in low-lying zones, such the Liangji Canal section [65]. Likewise, the groundwater storage recovery process may accelerate the dispersion rate of pollutants from hotspots to other unsaturated zones and raise the risk of groundwater and soil pollution, as illustrated in Fig. 2 [66,67]. Furthermore, the water diversion of the East Route has altered the community composition, richness, and diversity of flora and fauna in local aquatic ecosystems due to the change in the original hydrological regime. Although only limited effects are currently visible, this matter is a subject of concern for ecologists.

Diverse biotic groups respond differently to water diversion. The benthic macroinvertebrate communities in the impoundment lakes have experienced a typical degrade–recovery pattern [68]. Meanwhile, the dominant macrozoobenthoses in several lakes, such as Nansi Lake and Dongping Lake, have been modified, because the water transfer changed the hydrologic pulse and thus affected the water depth, quality, and heavy metal contents in sediments [69]. The lakeside macroinvertebrate community was more significantly affected in the early disturbing stage but recovered with greater resilience in the recolonized period compared with the community in the lake region. For the phytoplankton community, the total density and diversity index in Dongping Lake declined during the water-transfer period and then slowly increased when the diversion ended [70]. In contrast, Hu et al. [71] assessed the ecological health of impounded lakes along the East Route via the phytoplankton-based index of biological integrity and concluded that the water diversion greatly improved the ecological health status and stability of the lakes in dry seasons, although it changed the diversity and structure of the phytoplankton community. In the fish community, the abundance and biomass of the community showed a decreasing trend from the southern to northern sections along the East Route, which was closely related to the water quality patterns [72]. Vascular plants responded to the water diversion by changing their habitat. For example, emergent aquatic plants in Nansi Lake moved their habitat to northern regions with a water depth of less than 1.0 m, while the distribution of free-floating plants moved to the lakeshore area in response to water-level fluctuation [73]. Although different response behaviors have been observed among biotic groups, there is a general tendency for water diversion to potentially promote biotic homogenization among the involved water bodies by directly linking previously isolated catchments (Fig. 2) [72].

As a whole, the water-diversion approach exerts its influence on the transfer route regions. Water diversion through an open and isolated canal, such as the Middle Route, has almost no interaction with local water bodies and thus has a limited impact on regions along the diversion route. In contrast, water-transfer schemes of the East Route type that involve connecting existing water channels have been shown to have an important impact on the aquatic ecosystems along the route. Such a scheme can change the original hydrological regime of rivers and lakes, resulting in an artificial hydrological process; it can also modify water quality patterns and alter the structure of aquatic biotic communities. However, regardless of the type, all water-diversion schemes increase the risk of biological invasion by creating an "invasion highway" that facilitates the spread of non-native species. Moreover, both types of water-transfer routes modify organic matter transportation and microbial activities within the diversion channel, which are closely related to carbon mineralization and carbon dioxide (CO_2) fluxes [74]. This could be an interesting research field. For example, Xu et al. [75] estimated the CO_2 emission of the Middle Route at different stages and demonstrated the important role of water transfer in the food–energy–water–CO_2 nexus. More efforts are required to explore the influence of water diversion on carbon emissions, particularly in a global context.

3.3. Impacts on the recipient region

The recipient basin is normally regarded as a beneficiary of interbasin water transfer. The beneficial impacts include water resource addition, water quality improvement, and ecological flow increasement. The North China Plain (NCP) is the joint recipient region of the Middle and East Routes; the operation of the SNWD Project has greatly relieved its water shortage [76,77]. The two water-transfer routes have improved the water supply for agricultural, industrial, and domestic needs and have satisfied the ecological water demand in the NCP (Fig. 2) [78]. An evaluation of the eco-environmental benefits within the recipient region of the East Route suggested that urban green land, wetland ecosystems, and ecological conservation measures benefited from the water diversion, with urban green land receiving the highest eco-environmental benefit value of 3.767 billion CNY [79].

The efficacy of the SNWD Project as a solution to alleviate the groundwater overexploitation problem in the NCP has attracted widespread discussion [80–82]. Using a high-resolution hydrological model coupled with MODFLOW, Long et al. [83] showed the importance of the Middle Route for groundwater recovery in Beijing. According to their evaluation, the increased precipitation and reduced irrigation via policy formulation contributed to approximately 2.7 and 2.8 km^3 of groundwater storage recovery, respectively. Meanwhile, the diverted water to Beijing accounted for a major reduction in groundwater depletion, reaching up to about 3.6 km^3 during 2006–2018. Thus, the Middle Route has played a key role in alleviating the groundwater depletion and water-shortage issue in Beijing [82,84]. Similarly, Yang et al. [85] developed a high-resolution community water model to assess the interactions between water demand and availability by dynamically simulating surface water and groundwater interaction. Based on projected meteorological data for 2019–2050 derived from general circulation models, the results for different scenarios indicated that the water diversion could increase the groundwater storage over the NCP by 19 km^3 in 2050 and contribute to 37% of groundwater storage stability. Together with other water-management strategies, such as water-use reduction policies and additional diverted water of 0.3–0.5 km^3 per year through the East Route, the groundwater in the NCP is likely to rapidly recover in the coming decades [83].

When the diverted water reaches the recipient basin, it interacts with the local water body, changing the physiochemical characteristics of the water and altering the structure of the aquatic ecosystem. For example, the Miyun Reservoir is the receiving water body of the Middle Route. The water diversion has helped to recover the water resources in the reservoir but has significantly reduced the riparian buffer area and the total biomass in the riparian zone [86,87]. However, Zhang et al. [88] suggested that the impacts of water diversion on the local biotic community may not be of high importance in comparison with the effects from other compound factors, based on an evaluation of the influence of external measures on phytoplankton diversity in Dongping Lake, which is a recipient lake of the East Route, via a difference-in-differences model.

As mentioned earlier, biological invasion is another important concern for the recipient basin of water transfer. Interbasin water diversions connect biogeographic regions that were previously isolated, creating ''invasion highways'' for non-native invasive species (Fig. 2). Qin [89] observed an invasion of *Taenioides cirratus* (Blyth, 1860) (*T. cirratus*) and *Tridentiger bifasciatus* (Steindachner, 1881) (*T. bifasciatus*), which belong to the Gobiidae family, from the Yangtze River estuary to the linked lakes in the East Route, such as Luoma Lake, Nansi Lake, and Dongping Lake. The operation of the East Route probably directly caused the invasion of *T. bifasciatus* and enhanced the dispersal of *T. cirratus*. The colonization and invasion of the golden mussel, *Limnoperna fortunei* (*L. fortunei*), are currently major concerns for the Middle Route. *L. fortunei* readily attaches to the walls of water tunnels in high density with strong dispersal ability and increases biofouling risks in the Middle Route, especially in the context of climate change [90,91]. Fortunately, the northward-proliferation problem of schistosomiasis, which was a previous matter of concern, did not occur in both water routes [92]. However, it has been suggested that monitoring of *Oncomelania hupensis*, the host of schistosomiasis, should be continuously conducted, due to its acclimation to the recipient habitat [93]. Biological invasion through an artificial waterway, in combination with changes in habitat and water quality due to water diversion, will put pressure on native species populations, which could cause the extinction of local species [19,94]. Determining how to create an appropriate barricade to the ''invasion highway'' in order to prevent the dispersal of aquatic invasive species is a challenge for future scientists.

In addition to their impacts on the ecosystem of the receipt basin, water-diversion schemes modify the water-supply structure in the water-receiving area. Interbasin water diversion introduces new water sources into the drinking water distribution system. Red water problems can occur in the short term due to water source switching, which triggers variations in water quality and damages the original solid–liquid equilibrium in the pipe, resulting in enhanced iron release from corrosion scales (Fig. 2) [95–97]. Although the SNWD Project presented the risk of inducing water deterioration in local water-supply pipelines according to lab-scale experiments [98], it played an important role in the domestic water supply of Beijing, which alleviated the land subsidence problem and facilitated groundwater recovery [99]. A life-cycle assessment analysis on the multiwater sources of the receiving areas of the SNWD Project indicated that water supply via the Middle Route is the most sustainable option for Beijing and Tianjin, while reclaimed water reuse showed the highest sustainability for Jinan and Qingdao, which is the water-receiving region of the East Route [100]. However, the extreme weather events that have been projected for the future introduce uncertainty into the sustainable water supply of the SNWD Project [99].

4. Summary and implications

Interbasin water-transfer schemes provide an ultimate option for reconciling water scarcity and uneven distribution problems. These ''artificial rivers'' will account for an increasing proportion of the global hydrological network. Aside from social and economic concerns, the impacts of water transfer on local aquatic environments and ecosystems have attracted increasing attention. This review selected the typical SNWD as a study case and summarized its eco-environmental influences on donor and recipient basins, as well as the diversion route, to provide valuable experience for future engineering design. The key implications and suggestions are as follows:

(1) For the donor basin, the reduction in water resources triggers decreasing discharge in downstream river reaches, which can change the physicochemical characteristics of the water and the aquatic habitats of local biotic populations. In particular, the saltwater intrusion problem should be considered in advance if the water-withdrawal position is close to an estuary area. Integrated operation of water conservancy facilities is suggested to achieve a balance between the optimization of regional water resource allocation and ecological conservation.

(2) For the water-transfer line and two-side areas, different diversion approaches result in diverse influences. An excavated canal leads to the formation of an isolated aquatic ecosystem, which has limited effects on the local environment. In addition to monitoring the physicochemical characteristics of the water, the biological stability of diverted water requires attention, because a newly established ecosystem is normally highly vulnerable. Water diversion using existing river channels alters the original hydrological regime. Biotic groups respond to the change with a typical degradation-recovery pattern. In addition, water pollution control measures are strictly required to prevent the tributary input of pollutants into the water-transfer channel.

(3) Water transfer supplements the water resources of the recipient basin, supplying water for domestic use, agriculture, and ecological restoration. This partly alleviates the pressure on groundwater exploration, thereby preventing land subsidence. However, the soil salinization and accelerated pollutant-dispersion problems caused by groundwater storage recovery should be prevented in advance. In addition, water transfer removes biogeographic barriers and creates an ''invasion highway'' for invasive species. The subsequent bio-homogenization, together with changes in the aquatic habitat, presents a challenge for local biodiversity conservation. The frequent switchover of water sources in the recipient basin may also damage the stability of the water-supply system.

(4) Global climate change is bringing great uncertainties to precipitation and water resource distribution in both donor and recipient basins. Hence, the climatic stochasticity increases the difficulty of determining water-diversion amounts, which is becoming a chief task of hydrological researchers in this generation. In particular, the influence evaluation of the West Route should sufficiently consider climate risks, given that the water-donating area is sensitive to climate change. Ensuring stable operation under climate extremes will increase the resilience of the engineering project.

This work primarily focused on the environmental–ecological impacts of the operation of the SNWD. Environmental–geological influences, such as surface subsidence due to canal construction and soil salinization due to water leakage from channels, were not discussed in detail here. Still, a thorough understanding of the eco-environmental influences and implications of the SNWD Project is essential and valuable for future projects, such as the West Route. In the coming decades, further efforts are needed to systematically evaluate and predict the environmental and ecological influences of water-transfer schemes on basin and/or larger scales. Finally, an appropriate combination of water-diversion and water-saving measures, such as the recycling of reclaimed water, will greatly facilitate the establishment of a resilient and sustainable water system.

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Compliance with ethical guidelines

Hanlu Yan, Yuqing Lin, Qiuwen Chen, Jianyun Zhang, Shufeng He, Tao Feng, Zhiyuan Wang, Cheng Chen, and Jue Ding declare that they have no conflicts of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2023.05.012.

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