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Reconciling the strategic goals of irrigated food production, energy production with environmental flows under water transfer project in the Yellow River Basin

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Abstract. Reconciling the nexus relationship between water, energy and land (WEL) is critical for achieving sustainable development. Pathways to reconcile the WEL nexus in river basins remain unclear due to the lack of comprehensive assessments. In this paper, we provide a quantitative investigation using an engineering-economic optimization method to explore how and to what extent the water transfer project reconciles irrigated food production, energy production with environmental flows in the Yellow River Basin. The results show that, maintaining environmental flows at 30% of the river runoff will cause water for irrigation to be drained by energy production. Water transfer (~2.8 km^3/year) mitigates such trade-offs, decreasing water for the energy sector by 1.8% (0.14 km^3/year), and replenishing water for agriculture by 0.5% (0.09 km^3/year). Groundwater use decreases by 0.8% (0.13 km^3/year). Water transfer also builds synergies between water consumption and the economic costs of energy production, with these co-benefits in the lower reaches spilling over to the upper and middle reaches. Compared to irrigated food production, the operational costs of energy production are sensitive to water policies, implying that energy sector transformation is critical to sustainable pathways for reconciling the WEL nexus in the Yellow River Basin. Our study underscores the role of water transfer in alleviating water conflicts within the WEL nexus. Moreover, it provides valuable insights into transformative technological pathways toward a sustainable future in the Yellow River Basin and beyond.

1 Introduction

As the most essential resources for social and economic development, water, energy and land (WEL) are interrelated and interdependent. Reconciling the nexus relationship of WEL is a common path to achieving Sustainable Development Goals (SDGs) put forward by the United Nations (Zhang et al., 2019). The main idea of reconciling the WEL nexus is to mitigate trade-offs, build synergies, and improve resource utilization efficiency by resource allocation in the context of climate change and resource shortages (Cai et al., 2018; Conway et al., 2015; Kurian, 2017). However, some key issues, including how and to what extent the WEL nexus is shaped by climatic and anthropogenic changes, remain difficult to understand due to the lack of comprehensive assessments for the complex nexus relationship.

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A myriad of methods are available for engaged stakeholders in complex domains, yet expanding these practices to an integrated assessment of nexus issues raises new challenges (Wada et al., 2019). Underlying mechanisms and assessment tools for nexus issues are relatively less developed, making technology and policy discussions more uncertain for stakeholders who naturally think more separately on multi-sector issues. Combining nexus framing with technologies in optimization models not only allows the identification of pathways that build synergies among multiple sectors, but also provides a platform to explore technology options that balance WEL sustainability objectives (Parkinson et al., 2016). Many regional studies integrate optimization models with WEL systems (Li et al., 2023; Ma et al., 2024; Si et al., 2019), while less attention has been paid to long-term technology planning. The characteristic of identifying beneficial system states allows the optimization approach to be applied as a planning tool for future technology configuration (Webster et al., 2013). More importantly, technological costs serve as the bridge connecting ecological benefits to social-economic benefits, thus indicating the sensitivity to climatic and anthropogenic changes (Wada et al., 2019).

Reconciling food and energy production with environmental flows under water policies is of great significance to the WEL nexus of big river basins. The Yellow River is the second-longest river in China and is regarded as the cradle of Chinese civilization. With 67% of its basin situated in arid and semi-arid areas, the Yellow River occupies only 2% of China's total runoff, with its water resources per capita amounting to approximately 27% of the national level. Serving as the major source of freshwater, the Yellow River plays a critical role in the socio-economic development and ecological security of North and Northwest China. It supplies freshwater for domestic use to approximately 12% of China's population, for irrigating 15% of the country's agricultural area, and for the energy sector to more than 50 large and medium-sized cities, as well as important enterprises alongside the Yellow River (Si et al., 2019). Studies showed that, the renewable water resources of the Yellow River are likely to decrease over the next few decades but may increase by the end of the 21st century (Haddeland et al., 2014; Leng et al., 2015; Li et al., 2012). Meanwhile, anticipated socio-economic changes are expected to further amplify water demand (Liao et al., 2021; Wang et al., 2017; Yin et al., 2017). It remains a great challenge for water management to fulfill the multiple aspects of water demand in the Yellow River Basin in the context of climate change and human activities.

Unified water management and inter-basin water transfer have been implemented to promote orderly water use and alleviate water shortages in the Yellow River Basin. In 1987, the "87" Water Division Scheme of the Yellow River was carried out as the basis for water consumption targets of each province (Qiao, 2019). The scheme remained 21 km^3 of water annually as environmental flows (equivalent to 30% of the annual runoff of the Yellow River) to conserve water resources. To guarantee water security for key areas and key industries, the South to North Water Diversion (SNWD) Project was launched in 2002 and planned to transport ~45 km^3 of water annually from the humid south through three canal and pipeline systems (Long et al., 2020). The east and central routes of the project were completed in 2014, diverting ~2.8 km^3 of water annually from the Yangtze River to downstream regions of the Yellow River (He et al., 2005; Sun et al., 2021). While the water delivered to the Yellow River Basin accounts for only ~6% of the total planned water volume, the Comprehensive Planning of the Yellow River Basin (2012-2030) asserts that this project will significantly change the pattern of water

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resource allocation. Therefore, it is crucial to evaluate the influence of the SNWD project on the water system, as well as its relationships with energy and land systems.

Previous studies quantified the effect of the SNWD project on reducing water scarcity (Sun et al., 2021; Yin et al., 2020) and provided suggestions to readjust the water allocation plan in the Yellow River Basin (Chen et al., 2020; Jia and Liang, 2020; Wang and Lou, 2022). However, it remains unknown the impacts of water division and transfer on multiple sectors of the WEL nexus in the Yellow River Basin. Though existing studies have analytically and descriptively identified resource constraints and the implications of the WEL nexus in the basin (Peng et al., 2017; Si et al., 2019; Sun et al., 2020), most of these efforts focused on a single issue, such as the dynamics of water resources, with limited information regarding integrated water resources management within WEL nexus. In this paper, we incorporate water division and water transfer policies into the engineering-economic optimization method covering the water, energy and land-use sectors. We take into account policy background as constraints and technological costs as the optimization objective in the Yellow River Basin. The study aims to explore the influence of the water division scheme and the SNWD project on water conflicts among irrigated food production, energy production and environmental flows in the Yellow River Basin. To deep into this aim, more specific objectives of this study are addressed: 1) to investigate the role of water transfer in reconciling trade-offs relationship in the WEL nexus and improving resource utilization efficiency of water resources, and 2) to clarify the pathway of a sustainable WEL nexus, with detailed investment and operational costs of water allocation across sectors. Our purpose is to evaluate solutions that reconcile the strategic goals of irrigated food production, energy production and environmental flows under the water transfer project in the high-developed Yellow River Basin and beyond.

2 Methods and Materials

2.1 Integrated Water-Energy-Land nexus modeling

Developed by the International Institute for Applied Systems Analysis (IIASA), The NExus Solutions Tool (NEST) links a distributed hydrological model (the community water model, CWatM) with an engineering-economic resource supply planning model (MESSAGEix), to model water, energy and land-use systems (Vinca et al., 2020). NEST co-optimizes these three systems using a reference system scheme that features interactions across sectors (see Figure 1 for simplified system processes, Fig. S1 for detailed reference water system, and the work of Vinca et al. (2020) for detailed reference energy and land systems). The reference system scheme refers to the input-output supply chain representation that defines how technologies, resources and demands are connected in the model (Ilyas et al., 2022). Technologies connect resource flows between supply and demand, featured by input-output efficiencies (the rate at which a particular resource is consumed or produced during technology operations), costs (including operational and investment costs, i.e., the prices to run or invest a technology) and environmental impacts (e.g., greenhouse gas emission). Figure 1 conceptualizes the flows and stocks of water, energy and land systems.

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The water system constitutes processes of water diversion and withdrawal, wastewater collection and treatment, and environmental flow. Water diversion processes divert surface and groundwater to WEL sectors for use. Wastewater is collected from businesses and households, treated, and discharged into natural water bodies. Environmental flow refers to water that remains after use or is protected from human activities and flows to downstream. This process also generates hydropower. The energy system extracts fossil fuels or utilizes renewable resources to produce electricity, distributing it to WEL sectors for use. The land system consists of land-use change, irrigated or rainfed agriculture, food consumption, and residue. Dynamic food demand drives land-use change, influencing the scale of irrigation and rainfed agriculture. Residue provides biomass fuel for the energy system to generate electricity. Besides, the cooling process in the energy system and irrigation in the land system return a certain amount of water to replenish surface or groundwater. The interprocess flows are supported by technologies, for example, closed-loop and air cooling are often used as cooling technologies in arid and semi-arid areas to save water, while drip irrigation technology is promoted in the Yellow River Basin for its high irrigation efficiency.

Outputs from NEST include multi-sector transformation pathways (e.g., water for energy and land activities, energy needed to run processes in the water and agriculture sector, investment and operational costs for the technologies), all under technical-engineering constraints and political-societal considerations. For example, NEST optimizes water used by the energy and land sectors while expanding the power and water supply to meet future demands, with capacity expansion enabling the WEL nexus system to respond to climatic and anthropogenic changes, policy targets, resource constraints and so on.

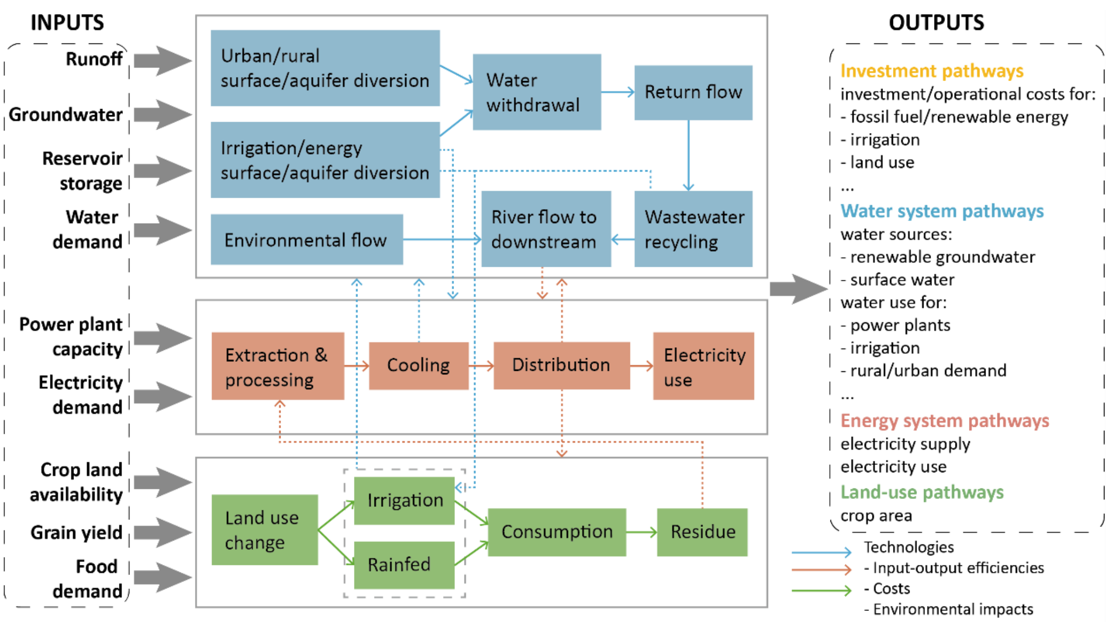

Figure 1. Boundaries and processes of the WEL nexus. The graph illustrates the simplified interactions among WEL systems, including inputs, interprocess flows, and outputs of investment, water, energy and land-use pathways, respectively. Dashed arrows represent

intersystem flows, indicating flows from processes of one system to processes of another system. All arrows stand for technologies that support WEL processes, characterized by input-output efficiencies, costs and environmental impacts.

2.2 Optimization

The pathways reconciling the WEL nexus, indicated by the future capacity and configuration of technologies, are determined by the optimization module in NEST. The objective of the optimization is to minimize the cumulative costs of WEL supply systems over the planning horizon while meeting the demands for resources and constraints on policies. Detailed cost accounting in the system includes technology investment, fixed and variable operational costs, and fuel costs. This type of cost-optimization model is common in national infrastructure planning (Liao et al., 2021; Peng et al., 2018; Webster et al., 2013). The objective function for linear programming is as follows:

$$min f(x) = \sum_{r,t} c_{r,t}^{T} x_{r,t} \delta_{r,t}; Ax \geq b \,, \quad (1)$$

where t is the time period index, r is the region index, x is the resolution vector, containing variables such as capacity and activity of technologies, c is the cost coefficient vector, δ represents the discount rate, calculating costs under different time period, A is the technical coefficient matrix, including supply-demand balances, technology capacity bounds, technology retirements and so on, and b is the right-hand side constraint vector, representing the limits of resources.

2.3 Spatial delineation

This study takes the Yellow River Basin in China's physical geographical divisions as the research area. The spatial range comes from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences, with an area of approximately 757,000 km^3, accounting for around 8% of China's territory. It includes 74 prefecture-level administrative units across nine provinces: Qinghai (QHA), Gansu (GSU), Ningxia (NXI), Inner Mongolia (NME), Shaanxi (SXI), Shanxi (JIN), Henan (HNA), Shandong (SDO), and Sichuan (SCH) (Fig. 2).

River basins serve as the most fundamental spatial units in the reference system scheme of NEST, because they delineate the flow direction of runoff, and water resources are the core to link the energy and land systems. In order to better display within-basin water flows and analyze the upstream-downstream water use dynamics, the river basins are disaggregated into sub-basins based on Digital Elevation Model (DEM) data. Considering WEL nexus is a comprehensive social-ecological system, the approach further intersects the sub-basin boundaries with provincial administrative boundaries. The final spatial delineation is defined as basin province units (BPUs). Each BPU is a node in the MESSAGEix reference system scheme, encompassing WEL resources and infrastructure, and stands for the basic unit for balancing supply and demand. Furthermore, to visually illustrate the flow direction of surface runoff in the Yellow River Basin, this study also draws a simplified river network based on a high-resolution flow direction dataset, namely Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (https://www.hydrosheds.org/products).

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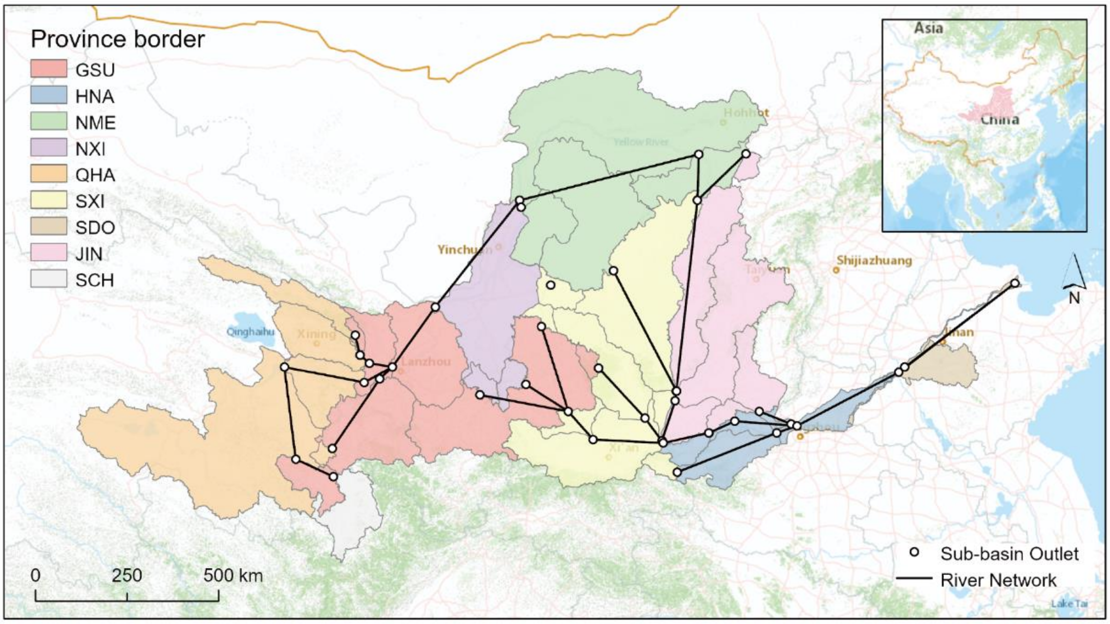

Figure 2. Delineation of spatial units in the Yellow River Basin. The graph depicts the basin delineated into basin province units (BPUs) with a reduced form node-link river network. Each white dot represents the outlet for the corresponding sub-basin; black line segment represents the river network connecting sub-basin outlets. GSU, Gansu; HNA, Henan; NME, Inner Mongolia; NXI, Ningxia; QHA, Qinghai; SXI, Shaanxi; SDO, Shandong; JIN, Shanxi; SCH, Sichuan**.**

2.4 Data sources

Two broad categories of data are needed in NEST: (1) historical and future data on resource use or availability, existing and planned technology capacities (Figure 1); and (2) other technology parameters, such as efficiency of resource use, costs, environmental impacts, and capacity factor. For future data, we use the SSP2 pathway to describe a world with development that occurs at rates consistent with historical patterns, implying moderate levels of investment in human capital, technological change, and economic growth (Jones and O'Neill, 2016). 2050s is selected as the future horizon for our optimization for two reasons: 1) technologies are expected to have a 20 to 30 years lifetime, meaning that power plants constructed in 2020 would likely be retired between 2040 and 2050, and 2) China has committed to reaching its peak total CO_2 emissions before 2030 and achieving carbon neutrality before 2060, thus the development trajectory until 2050 to 2060 is of particular importance and great concern.

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2.4.1 Water system

Water withdrawal and consumption for crop, industry, urban and rural were taken from Khan et al., 2023 (covering period: 2010-2050, spatial resolution: 0.5°). Existing reservoirs' capacity, age and location during 1990-2020 were acquired from the Georeferenced Global Dams and Reservoirs Dataset (GeoDAR) (Wang et al., 2022). Planned reservoirs and power plant capacity during 2020-2030 were collected from the Comprehensive Planning of the Yellow River Basin (2012-2030). Evaporation losses, surface runoff and groundwater recharge were downloaded from the Inter-Sectoral Impact Model Intercomparison Project Database (ISIMIP) (covering period: 2010-2050, spatial resolution: 0.5°) (https://data.isimip.org/search/tree/ISIMIP3b/OutputData/water_global/).

2.4.2 Energy system

Electricity consumption for industry, urban and rural with 1-km spatial resolution was obtained from Chen et al., 2022. Future electricity consumption was projected by population and GDP. Projections of GDP in China were collected from Huang et al., 2019. Power plant capacity during 1990-2020 was sourced from the Global Power Plant Database (https://datasets.wri.org/dataset/globalpowerplantdatabase).

2.4.3 Land system

The cropping systems include cotton, pulses, maize, rice and wheat. Crop area and crop yield of five crop types with 10-km spatial resolution were from the Global Agro Ecological Zones Database (GAEZ) (https://gaez.fao.org/). Future crop demands were predicted by production level and population. Production level at the country scale was published by the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) (https://www.fao.org/faostat/en/). Population from 2000 to 2050 was obtained from Jones and O'Neill, 2016 with a spatial resolution of 0.125 degree.

2.4.4 Technology parameters

The estimation of technology parameters referenced a number of different sources (SI, Tables S1-4). Costs of electricity supply technologies are from Ye, 2013 and Webster et al., 2013. Capacity factor of electricity supply technologies is from Liu et al., 2018. Water use intensity for power plants is obtained from Parkinson et al., 2016 and Liao et al., 2021. Additional parameters of power plant technologies not included in aforementioned references are taken from Vinca et al., 2020. The water supply technologies include groundwater withdrawals, surface water withdrawals and wastewater treatment. Costs for surface and groundwater are accounted for by tracking the electricity used. Technologies for the land system are crop and irrigation technologies. Crop prices are obtained from Food and Agriculture Organization (FAO). Irrigation efficiency for drip, sprinkler and surface irrigation is from Rosa, 2022.

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2.5 Scenario settings

The model is applied across three scenarios to explore trade-offs and synergies under water allocation policies, namely baseline, EFs and SNWD scenarios. The impact of constraining environmental flows on water used by the energy and land sector is explored by comparing the EFs scenario with the baseline scenario. A deeper investigation into how and to what extent the water transfer project reconciles irrigated food production, energy production with environmental flows is explored by comparing the SNWD scenario with the EFs scenario.

In detail, a baseline scenario explores the continuation of current trends and no water policy interventions. We assume the basin has sufficient water to meet demands for environmental flow, food and energy production. The baseline scenario reflects the basic ecological and socio-economic situation of the Yellow River Basin, so accuracy of historical data and reasonability of future data are crucial. An EFs scenario depicts constraining environmental flows for ecological use according to the water division scheme regulated by the Comprehensive Planning of Water Resources of China. In this scenario, environmental flows account for nearly 36.21% of runoff in the Yellow River Basin (Jia and Liang, 2020). Maintaining environmental flows is one of the frequently used methods to protect surface water resources, however, it could also exacerbate the shortage of water supply for human activities. A SNWD scenario describes the implementation of the east and central routes of the SNWD project, diverting ~2.8 km^3 of water annually from the Yangtze River to downstream of the Yellow River (He et al., 2005; Sun et al., 2021). This scenario aims to elucidate the effect of this major water diversion project on alleviating water stress and promoting sustainable water conservation in the Yellow River Basin. The sets of scenarios are outlined in Table 1.

Table 1. Scenarios settings for water division and water transfer policies**.**

Policies	Scenarios		
	Baseline	EFs	SNWD
Water Division Scheme	No environmental flows constraints.	Environmental flows account for 36.21% of runoff.	Environmental flows account for 36.21% of runoff.
South-to-North Water Transfer Project	No water transfer.	No water transfer.	The project diverts ~2.8 km^3 of water annually to downstream of the Yellow River.

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3 Results

3.1 Trade-offs of water system pathways within the WEL nexus

Among the WEL sectors, we focus on water system pathways in response to water policies, as water resources form the foundation for energy and food production in the Yellow River Basin (Peng et al., 2017). Water sector changes are categorized as alterations in water sources and water final use. Figure 3 depicts water withdrawals by three kinds of water sources and water end use by different sectors at the provincial scale from 2020-2050 for baseline and EFs scenarios. Given that the changes in the SNWD scenario are not prominently reflected in yearly values similar to Fig. 3, the SNWD scenario compared to the EFs scenario regarding water sector changes for multi-year averages is presented in Fig. 4. We calculate percentage changes to clearly demonstrate the influence of the water diversion project on the water sector in the Yellow River Basin.

In the EFs scenario, the entire basin reduces surface water withdrawals in all modeled years compared to the baseline scenario. Consequently, renewable groundwater is utilized as a swap to ensure water demands. To be more specific, the conservation of environmental flows results in an increase in renewable groundwater use (+108.72% annually) and a decrease in surface water use (-42.2% annually) in the Yellow River Basin. From Fig. 3, it is evident that the highest increase in renewable groundwater withdrawals occurs in SXI, followed by JIN and NME. In terms of water end use, both the land and energy sectors are affected by environmental flows constraining. The water use for flood irrigation decreases noticeably in NME and HNA. In contrast, the water use for power plants increases, particularly noticeable in the middle and lower reaches of the Yellow River. Such trade-off explains that the energy industry would drain the water used for agricultural irrigation in the basin if available surface water curtails.

The water transfer project could save renewable groundwater by 0.13 km^3/year for the entire basin, observably in QHA, NXI and HNA (SNWD scenario vs. EFs scenario). In these areas, the water withdrawal is replaced by surface water. Such mitigation is predominantly observed in irrigation districts, such as NXI and NHA, both well-known as major grain production bases in China, rather than in energy production districts, such as SXI and JIN, recognized as coal-rich regions and important energy bases. This suggests that the model considers it cost-optimal and demand-satisfactory for the energy sector to continue utilizing groundwater, and the SNWD project still has a limited effect on controlling this situation. We highlight two types of water final use: flood irrigation representing water needed for irrigation in the land sector, and power plants representing water needed for power generation in the energy sector. As shown in Fig. 4, water used for flood irrigation improves by 0.54%, and for power plants declines by 1.8% for the entire basin relative to the EFs scenario after the implementation of the SNWD project. It is worth noting that the most significant change occurs in SDO, where water for power plants decreases by nearly 35% compared to the scenario that constrains environmental flows.

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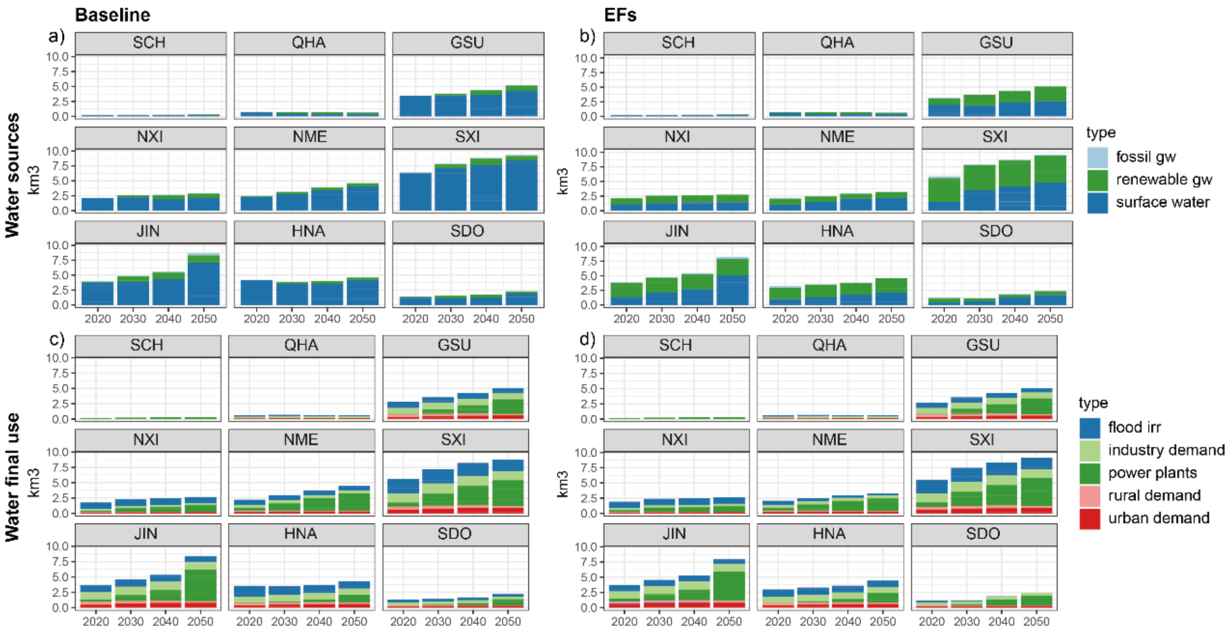
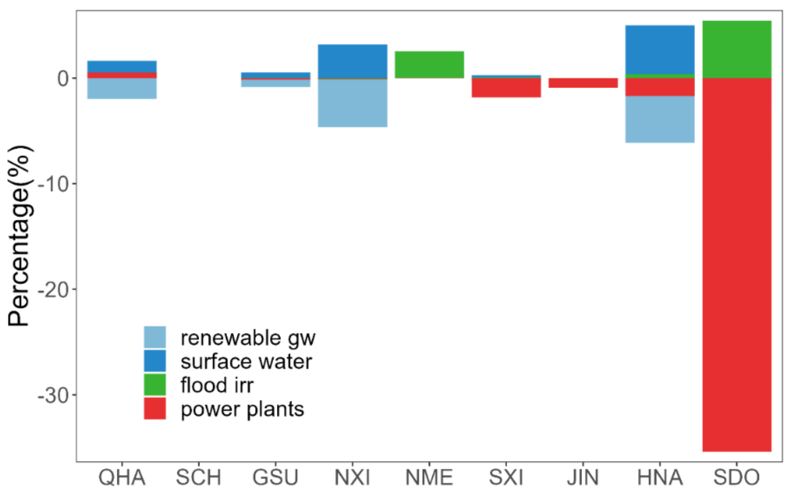


250 **Figure 3.** Boundaries and processes of the WEL nexus. The graph illustrates the simplified interactions among WEL systems, including inputs, interprocess flows, and outputs of investment, water, energy and land-use pathways, respectively. Dashed arrows represent intersystem flows, indicating flows from processes of one system to processes of another system. All arrows stand for technologies that support WEL processes, characterized by input-output efficiencies, costs and environmental impacts**.**



255 **Figure 4.** The SNWD scenario compared to the EFs scenario of multi-year average from 2020 to 2050 for water sources (renewable groundwater and surface water) and water final use (flood irrigation and power plants) in the Yellow River Basin**.**

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3.2 Spillover effects of water transfer project

The SNWD project was designed to divert water to the downstream areas of the Yellow River. However, we also find that the areas benefitting from the SNWD project extend to the upper and middle reaches of the Yellow River (Fig. 4 and Fig. 5).

Renewable groundwater is reduced not only in the downstream Yellow River Basin, but also in the upstream and middle reaches (Fig. 4). Since diverting water to downstream areas can provide additional water resources for HNA and SDO, effectively implementing environmental flows. As a result, HNA and SDO have extra surface water available for the land and energy sectors, reducing the need for regions in the upper and middle reaches to retain sufficient water resources for downstream areas according to the previous environmental flow standards. The replenishment of water for irrigation and the decline of water for power plants also occur in other provinces besides the downstream Yellow River Basin. For instance, NME sees a significant increase in irrigation water use, second only to SDO, and the decrease in water use for power plants in the middle and lower reaches is relatively higher. These comparisons indicate that the water transfer project has spillover effects on enhancing environmental flows from the perspective of the WEL nexus.

Investment and operational costs for technologies responding to the water transfer project exhibit a similar pattern. Reduced costs for fossil-fuel-based electricity generation under the SNWD scenario are mostly observed in SXI, JIN and SDO (Fig. 5). While SDO is located in the lower reaches of the Yellow River, SXI and JIN are in the middle reaches, both well-known as important energy bases in China. This reduction is in accordance with the decline in water use for power plants after transferring water (Fig. 4), suggesting that the water transfer project could build synergies between water use and economic costs for the energy sector. Moreover, such co-benefits not only happen in downstream, but also influence upstream areas.

3.3 Critical role of the energy sector under water allocation policies

It has been demonstrated that water supply planning models are sensitive to energy prices (Matsumoto and Mays, 1983; Scott, 2011), and likewise electricity generation planning models are sensitive to water constraints (Vliet et al., 2013; Webster et al., 2013; Welsch et al., 2014). However, incorporating the land sector into the water-energy system helps us perceptually compare the roles of the energy and land sectors in responding to water allocation policies. Figure 5 presents the difference in the average investment and operational costs per year of the EFs scenario compared to the baseline scenario, and the SNWD scenario compared to the EFs scenario for each province.

In the EFs scenario, meeting the minimum environmental flows under the water division scheme results in an increase of US$0.29 billion/year in investment costs and US$1.94 billion/year in operational costs compared to the baseline scenario. The investment costs grow slightly while the operational costs grow significantly, implying that what mostly changes is the operation process of technologies rather than their scale and pattern under this scenario. Costs on the electricity grid, fossil energy and renewable energy see significant increases, rising by 8.32%, 36.15% and 9.73%, respectively. Compared to the land sector, operational costs for the energy sector are more prone to change when constraining environmental flows. This

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implies a ripple effect where economic costs also proliferate as water stress grows for the energy sector in the Yellow River Basin, leading to the application of energy production technologies that consume less water but incur high expenditures. At the provincial scale, JIN and SDO are mainly affected, both located in the middle and lower reaches of the Yellow River. In contrast, maintaining environmental flows causes a slight decrease in irrigation costs, specifically in NME, HNA and SDO.

In the SNWD scenario, the entire Yellow River Basin requires an additional investment of US$0.03 billion/year compared to the EFs scenario. Most added investment costs are allocated to irrigation technologies, because the water transfer project could alleviate agricultural water stress, mainly in HNA and SDO. Both provinces are in the lower reaches of the Yellow River, where the SNWD project transmits water. At the same time, the Yellow River Basin saves around US$0.2 billion/year in operational costs for the electricity grid and fossil energy. Notably, the operational costs of the electricity grid in SDO decrease substantially by nearly US$0.14 billion/year, indicating the stress on power transmission has been alleviated following the project's implementation. Similar to the comparison between the EFs and baseline scenario, it is clearly shown that operational costs for the energy sector are more sensitive than those for the land sectors.

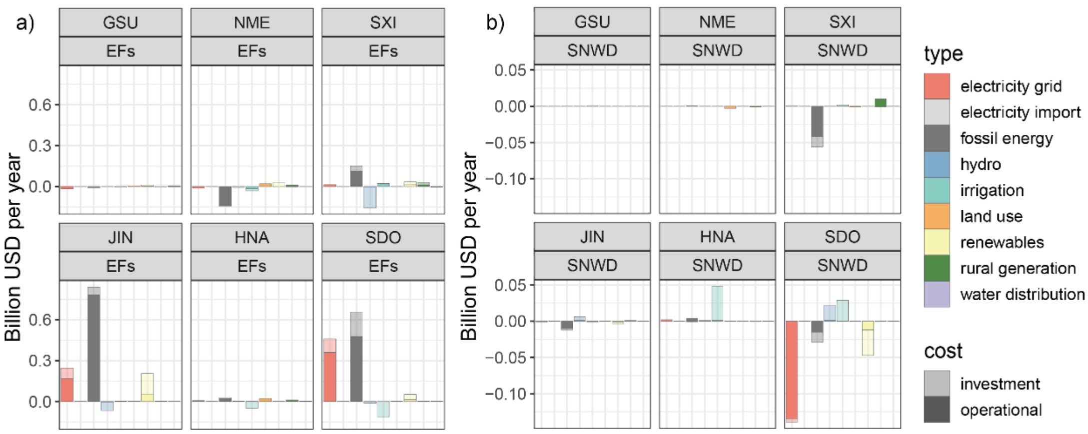

Figure 5. Difference in annual investment and operational costs between scenarios. a) Difference in expenditure of the EFs scenario compared to the baseline scenario. b) Difference in expenditure of the SNWD scenario compared to the EFs scenario. Costs are indicated in USD2010 values. Types of technologies: electricity grid, electricity transmission and distribution; electricity import, interprovincial electricity import; fossil energy, energy generation from fossil fuels; hydro, large and small hydropower; irrigation, irrigation technologies (flood, drip, sprinkler and canals); land use, land cost, machinery and fertilizers; renewables, solar, wind or biomass generation; rural generation, rural diesel or solar energy production; water distribution, water extraction, diversion and distribution.

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4 Discussion

4.1 Impacts of the SNWD project

Various approaches can be used to recover water storage, including increasing inputs and/or reducing outputs. Water transfer projects, typically the SNWD project, are approaches that increase inputs from humid regions to arid regions. Generally, the SNWD project has positive impacts on water recipient basins. From the perspective of water sources, recipient basins can benefit from improved environmental flow conditions (Li et al., 2021; Zhen et al., 2023). The Chief Executive of China's SNWD Corporation Ltd. Jiang, Xuguang, stressed that the fundamental goal of the SNWD project is to improve and restore the ecological environment of the Huang-Huai-Hai Plain and Jiaodong region (Fu, 2021). As a result, ~43% of the SNWD water delivered to the Beijing system is now classified as ecological water (Zhen et al., 2023). Notably, nearly half of key ecological water diversion projects in China since 2000 have been associated with the Yellow River Basin, and water recharging for ecosystem restoration would be a fast-growing water allocation category. The project also helps with the recovery of groundwater storage (Long et al., 2020; Xu et al., 2024; Zhang et al., 2020). For example, water diverted to Beijing reduced cumulative groundwater depletion by ~3.6 km^3 during 2006-2018 (Long et al., 2020), and groundwater storage saw an increasing trend (+0.3 km^3/year) in North China Plain during 2015-2018 (Zhang et al., 2020). Given the disparity in water transfer volumes to different areas (~7.0 km^3/year to North China Plain versus ~2.8 km^3/year to the Yellow River Basin), the decreasing trend of groundwater use in our results are in consistent with previous studies.

Regarding multi-sector water use, the SNWD project was initially designed to transfer water for domestic and industrial uses, leading to indirect effects on agricultural water use in water recipient areas, and there is a lack of a uniform viewpoint. For instance, Wang and Liu used an agricultural prices, land use and environment model, and found that increasing the amount of water transfer from current level to full capacity of the whole SNWD would increase irrigation water use in water receiving basins by 0.4%~4.67% (Wang and Liu, 2021), which shares similar results with our study. In contrast, results from an econometrics model showed that the scale and proportion of agricultural water use in the receiving areas have decreased after the implementation of the SNWD project (Xu and Yao, 2022; Xu et al., 2024). These different conclusions come from various interpretations of mechanisms and methodologies. Research indicating a decline in agricultural water use tends to emphasize direct impacts, such as shifts in crop patterns, whereas our study focuses on the indirect impact, which is the indirect return of agricultural water through water supply of the project. Unlike the relatively straightforward interpretation of impacts on water sources through established hydrological models, assessing the effects on agricultural and industrial water use requires a more complicated nexus model. Compared to other methods targeting this focused issue, our multi-sector optimization method, combining a hydrological model and engineering-economic resource planning, has distinct advantages and irreplaceability. It not only captures the interconnections among water, energy, and land sectors, but also uses river networks to connect upstream to downstream areas, having the potential to analyze spillover effects.

4.2 Vulnerability of energy production to water policy

Our study demonstrates that the economic costs of the energy sector are prone to fluctuate in response to water policies compared with the land sector, indicating the critical role of energy production in the sustainable pathways of the WEL nexus in the Yellow River Basin. Actually, water constraints have already impeded energy development in China. Liao et al. found that water risks are greatest in northern China, where 35% to 60% of regional coal-fired power capacity is threatened by cooling water shortages during months of low flow from December to June (Liao et al., 2021). Spatially, seven hotspots in northern China are highlighted as power-vulnerable to water scarcity, more than half of which are located in the Yellow River Basin (Zheng et al., 2016). To cope with water shortage risks, thermoelectric power plants in the north commonly rely on groundwater and reclaimed water from industrial and municipal wastewater. According to the China Electricity Council, 16.2% and 12.2% of China's coal power plants' current water usage are from groundwater and reclaimed water respectively (China Electricity Council, 2015).

The Yellow River Basin has enormous thermoelectric power plants, with over half of its electricity consumption still reliant on coal. Given the water scarcity of the Yellow River Basin, closed-loop cooling systems that require relatively minimal water withdrawals are prevalently used (Liao, 2020). Though closed-loop cooling systems require less water than open-loop ones that are widely used in southern China, coal-fired power generation remains inherently water-intensive. Regions rich in coal, such as SXI and JIN, witness a proliferation of groundwater withdrawals under scenarios involving environmental flow constraints.

In order to improve the resilience of the energy sector towards water shortages, transitioning power plants to renewable energies in addition to inter-regional water transfer projects is advocated. The Yellow River Basin boasts abundant wind, light and water energy resources, making it well-grounded to develop renewable energy industry. Western Inner Mongolia, for instance, is one of China's nine large-scale wind power bases, with ongoing transmission project construction. Additionally, more than half of China's 19 leading photovoltaic power generation bases are located within or near the Yellow River Basin. The hydropower bases in the upper and middle reaches of the Yellow River were already listed as the thirteen largest hydropower bases in our country as early as the 1980s (Ma and Zhang, 2020). Hence, the basin holds enough potential for expanding the utilization of renewable energies, and these options include, but are not limited to, natural gas combined cycle (NGCC), wind power, solar photovoltaics (PV) and geothermal heat pumps.

4.3 Sensitivity analysis

Integrated assessment models are subject to different types of uncertainty, which can cumulate and therefore require validation. However, it is generally difficult to validate model results when dealing with future scenarios in the scope of policy analysis due to the lack of survey data. Here, we perform a sensitivity analysis and specifically explore uncertainties surrounding total costs, water withdrawals and uses, energy production and land use by varying the efficiency and investment costs across an arbitrary range (–25%, +25%). Figure 6 depicts the percent change under the baseline scenario in

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response to a variation in input parameters. It is noteworthy that groundwater withdrawals are particularly sensitive to input parameters, owing to the vulnerability of groundwater in semi-arid areas. Generally, most outputs are strongly affected by the variation of sector-related parameters, such as energy production is sensitive to capacity factor and investment costs of power plants, and water use for flood irrigation is strongly affected by the water efficiency of irrigation technologies. The plot also shows some significant cross-sectoral feedback, for instance, changes in energy efficiency and investment costs impact power plants' water use, thus influencing surface water and groundwater withdrawals, and irrigation efficiency impacts land use. Multiple parameters affect total costs and the variations seem relatively steady.

In doing this study, we also find that runoff, electricity demand, crop water consumption and historical technology capacity are key to model outputs in the Yellow River Basin. Natural runoff indicates the available surface water resources, and groundwater recharge refers to the available subsurface water, both of which are important components of the water balance and directly influence the water supply for the entire basin. Electricity demand represents the amount of electricity that needs to be generated, thus affecting water consumption from power plants. It is complex to quantify crop water consumption in this model because crops are required to be subdivided into categories such as wheat, rice, maize, pulses and cotton, each of which mainly consume water in different months. Historical technology capacity refers to the capacity of technologies that were already built before the 2020s. This data primarily affects the technology pattern in the future, and consequently changes the investment and operational costs. For example, to meet the increasing demand for electricity generation, new power plants need to be placed while old ones remain in use until retirement.

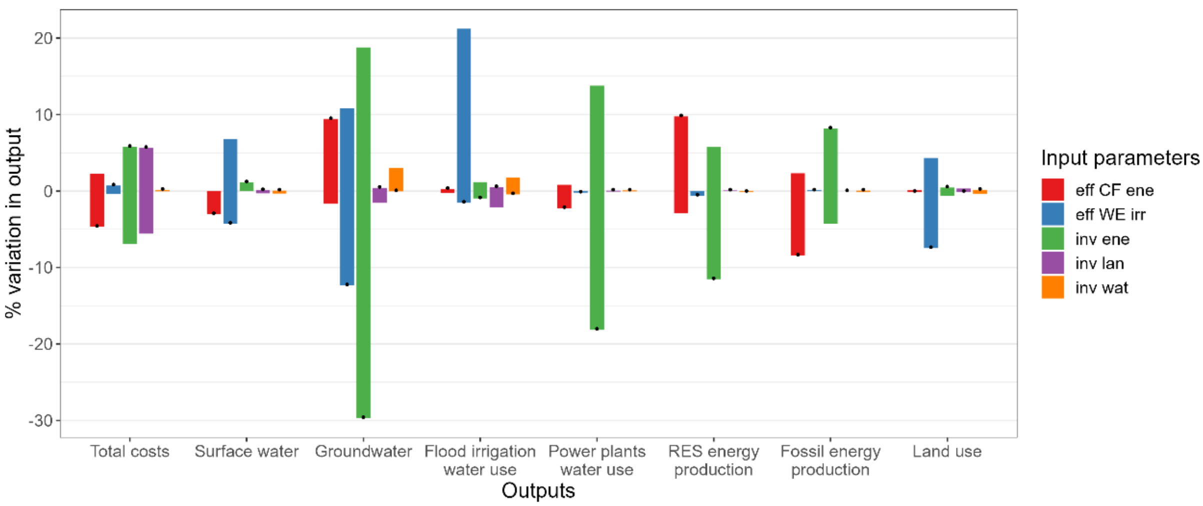

Figure 6. Changes of model outputs in response to a variation (−25%, +25%) of input parameters, namely power plants' capacity factor (eff CF ene), irrigation technologies' water efficiency (eff WE irr), investment costs of power plants (inv ene), irrigation and land management (inv land) and water distribution/treatment (inv wat). The outputs refer to average yearly values from 2020 to 2050 for total system costs, surface and groundwater withdrawals, water uses for flood irrigation and power plants, energy production from renewable and non-renewable sources, and land use for agriculture. The black dots show the outputs corresponding to +25% variation in inputs.

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5 Conclusion

This study uses an integrated WEL optimization model to explore sustainable pathways of water use by energy and land sectors subject to policy constraints on water regulation in the Yellow River Basin. We put emphasis on the water sector within the WEL nexus context under consideration of the water crisis in the Yellow River Basin, also in light of the unique role of water in WEL system analysis. Apart from that, we also focus on the investment and operational costs of technology development supporting water policies, as this is our optimization objective and the bridge connecting ecological benefits to social-economic benefits.

The results highlight pathways to reconcile the nexus relationship among irrigated food production, energy production and environmental flows in response to water management policies. Under the protecting environmental flows policy, water used for irrigation is drained by energy production since surface available water curtails, putting renewable groundwater at further risk. Renewable groundwater use nearly doubles, and total costs of fossil energy technologies are driven up from US$3.65 billion/year to US$4.89 billion/year. Compared to the land sector, operational costs for the energy sector are more sensitive to water policies. After implementing the east and central routes of the SNWD project, the above-mentioned circumstances could be alleviated. Water for energy generation and agriculture production decreases and is replenished respectively, and renewable groundwater use declines by 0.13 km^3/year. Such mitigation occurs not only in the lower reaches of the Yellow River, where the project diverts water, but also in the middle reaches, indicating that the water transfer project has spillover effects on improving the environmental flows from the perspective of the WEL nexus. The water transfer project also leads to a decrease in operational costs on electricity transmission in SDO by nearly US$0.14 billion/year. Even though the water transfer project has positive effects on alleviating water stress in the Yellow River Basin, these effects are still limited and further water regulation is needed.

Data availability. Data will be made available on request.

Author contribution. **Yichu Huang**: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Visualization. **Xiaoming Feng**: Writing – review & editing, Conceptualization, Supervision, Project administration, Funding acquisition. **Chaowei Zhou**: Methodology. **Bojie Fu**: Supervision, Project administration, Funding acquisition.

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