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Evaluating Spatiotemporal Variations in the Impact of Inter-basin Water Transfer Projects in Water-receiving Basin

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Abstract
Inter-basin water transfer (IBWT) has been widely applied to solve the water resource crisis in water shortage areas, and its impact on the ecological environment of water-recipient areas has gained increasing attention in recent years. In this study, based on the Soil and Water Assessment Tool (SWAT) model, the average monthly channel flow and water environmental capacity (WEC) with or without IBWT projects were simulated and quantified in the Fenhe River basin of China. The results showed that the IBWT projects significantly improved the flow of 63% of channels, and the increase in the dry season (80%) was much higher than that in the wet season (20%). The changes in the ideal WEC were positively correlated with the channel flow, while the remnant WEC showed different change trends in different channels and seasons. Spatially, the remnant WEC decreased in a few upstream channels and increased in the downstream channels. Seasonally, IBWT projects had different seasonal effects on the remnant WECs of total nitrogen (TN) and total phosphorus (TP). In the dry season, the remnant WEC of TN decreased by 2% after IBWT, while the remnant WEC of TP increased by 140%. In the wet season, the remnant WEC of TN increased by 4%, while the remnant WEC of TP decreased by 80%. Through a long-term simulation of IBWT projects, this study reduced the uncertainties caused by random changes in the hydrological environment. These results could provide effective guidance for management after the construction of IBWT projects.

Keywords SWAT model · Ecological flow · Water environmental capacity · Temporal-spatial impact

1 Introduction

The extremely uncoordinated distribution of water resources with land, population, and socioeconomic centers is a common phenomenon in many countries, and the growing demand for water further increases the water pressure (Biswas 2004; He et al. 2014;

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Tang et al. 2014). Many countries have explored effective water resource utilization methods, among which inter-basin water transfer (IBWT) projects are an effective engineering measure to realize the rational allocation of water resources (Wang et al. 2016; Zhu et al. 2008). An IBWT project can redistribute water resources in time and space according to human will, and improve the watershed environment while meeting water demand (Sinha et al. 2020). However, improper scheduling of IBWT may lead to a waste of water resources and cause damage to the ecological environment of the water diversion and receiving areas (Barnett et al. 2015). Therefore, it is essential to quantify the impact of IBWT at the basin scale to fully improve the water utilization efficiency of IBWT projects and avoid ecological environment damage.

A real-world IBWT project includes the spatiotemporal transfer of water quantity and pollution loads (Wang et al. 2016). Although many studies have quantified the impact of IBWT on river flow and pollutant concentrations, there is a lack of effective guidance for environmental improvement in water-receiving area (Gu et al. 2017; Karandish et al. 2021). As the key to maintain ecosystem health, the ensuring of river ecological flow is becoming a hot topic in scientific research and management (Cheng and Li 2018; Cheng and Li 2021; Yan et al. 2018). Quantifying the impact on the satisfaction of the ecological flow is necessary to assess the effectiveness of IBWT projects. Meanwhile, the IBWT projects include the dual transfer of water quantity and pollution load, which significantly changes the water environmental capacity (WEC) of each channel in the receiving area. As the core content of water quality target management, the spatiotemporal change of the WEC is very important to the basin pollution control (Wang et al. 2019; Xie et al. 2014). To fully describe the ecological environment changes in water-receiving basin, it is necessary to quantify the impact of IBWT projects on both river ecological flow and the WEC.

In recent years, a great number of studies on the impact of IBWT have been carried out at the basin scale, and the coupled water quantity and quality models are the most commonly adopted method (Gohari et al. 2013; Ma et al. 2020). These coupled models evaluated the impact of IBWT based on the results of basin outlet or individual river channels and sections (Manshadi et al. 2015; Zhou et al. 2017). However, due to the differences in the hydrological status and pollution status of channels, the impact of IBWT projects on various channels is different, and may even be opposite (Woo et al. 2021). In the case of multiple water supply projects, owing to the uneven distribution of water supply points and replenishment amount in time and space, the impact of IBWT on all channels is more complex (Gu et al. 2017). Revealing the spatial difference in the impact of IBWT projects on each channel within a basin is a key issue to be resolved.

In addition, because of the continuous operation of IBWT projects after construction, the impacts on the evapotranspiration, water quality, and runoff characteristics of a basin are long-term and sustained (Rogers et al. 2020). Previous studies have mostly focused on the ecological assessment and social impact assessment of IBWT projects before or during construction, selecting only one period or one year as the study period, which could underestimate the impact of IBWT on the receiving area (Barbosa et al. 2021). Compared with the short-term local-scale analysis of water diversion projects, long-term series simulations at the basin scale will provide a more comprehensive and reliable output (Rogers et al. 2020). To improve the impact analysis accuracy of IBWT projects, a long-term hydrological model should be used to simulate the water quantity and quality of the receiving area on a continuous time series.

Taking the Fenhe River basin as the research area, this study used the Soil and Water Assessment Tool (SWAT) to model IBWT projects and quantify their impact on the water quantity and quality of the receiving area in a long time series. The main goals of this study were to (1) establish the SWAT model of the Fenhe River basin based on historical natural and measured hydrological data; (2) confirm the applicability of the SWAT model to evaluate the long-term, continuous impact of IBWT projects; and (3) quantify the spatiotemporal impacts of IBWT projects on the ecological flow and WEC of the receiving area.

2 Materials and Methods

2.1 Study Area

The Fenhe River (110.30–113.32° E, 35.20–39.00° N) is the second largest tributary of the Yellow River (Fig. 1), with a length of 716 km and drainage area of 39471 km^2, which accounts for 25.3% of the total area of Shanxi Province (Zhang et al. 2013). According to the natural topographic characteristics of the basin and the hydrological conditions of different river channels, the main stream of Fenhe River can be divided into three parts: upstream, midstream and downstream (Fig. 1). The annual precipitation in the Fen River basin varies considerably, and the wet season is from May to October. As the most concentrated area of economic development in Shanxi, the gross domestic product of the Fen

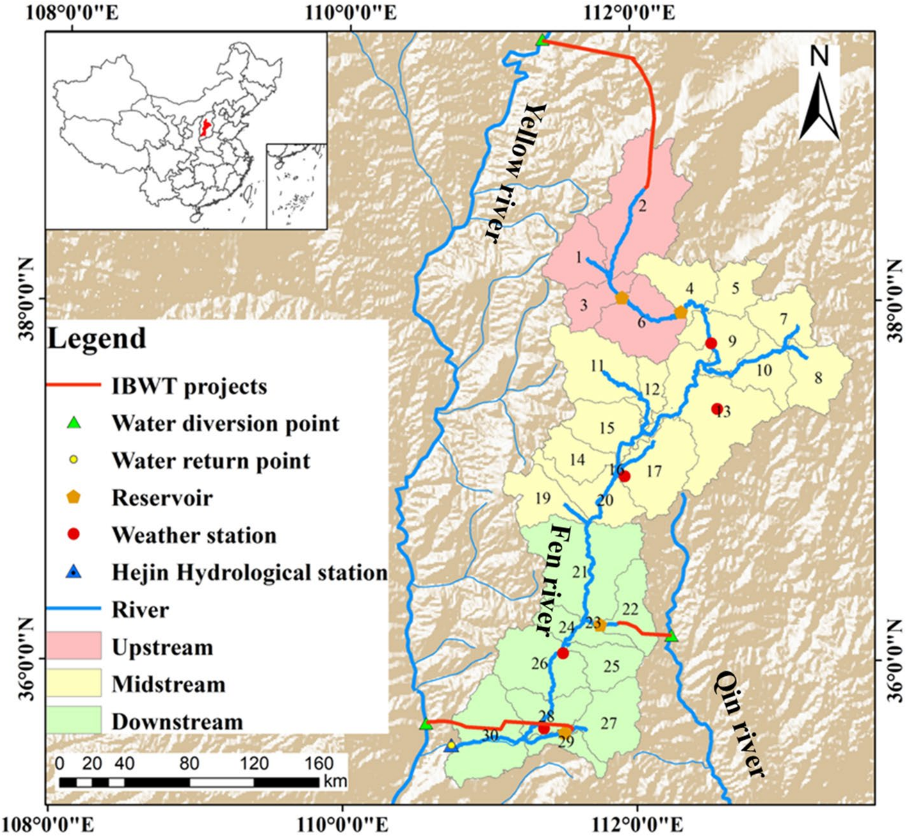


Fig. 1 Location of the study area

River basin accounts for 45% of that of the province (Sun et al. 2020). However, due to unreasonable utilization, in the past 50 years, problems such as declining groundwater levels, drying-out of the river, and increasing water pollution have become prominent in the watershed (Zhao and Chen 2015).

In 2008, Shanxi Province launched IBWT projects to improve the ecological environment of the Fenhe River basin. The existing IBWT projects include the Wanjiazhai Yellow River diversion project, the Hechuan water diversion project, and the Yumenkou Yellow River diversion project (Fig. 1). Currently, water resource allocation is mainly based on the principle of alleviating the uneven distribution of water resources during the year, without considering the ecological environmental impacts of these IBWT projects (Yuan et al. 2018).

2.2 SWAT Model and Inter-basin Water Transfer

The SWAT is a semi-distributed, physically based, and time-continuous model that has been widely used to simulate watershed hydrological processes and water quality (Teshager et al. 2017). It was developed by the United States Department of Agriculture's Agricultural Research Service (Arnold et al. 1998). The major simulation components of the SWAT model include hydrology, soil erosion, nutrient transport and transformation, management practices, and channel processes. The water balance equation is the basis of the SWAT model simulation of the hydrological process:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \tag{1}$$

where SW_t (mm) is the final soil water content; SW_0 (mm) is the initial soil water content on the ith day; t (d) is time; R_i (mm) is the amount of precipitation on the ith day; Q_i (mm) is the amount of surface runoff on the ith day; ET_i (mm) is the evapotranspiration amount on the ith day; P_i (mm) is the amount of percolated water on the ith day; and QR_i (mm) is the amount of return flow on the ith day.

The IBWT projects include the spatial and temporal transfer and allocation of water resources, and space allocation is realized through the water diversion points scattered in the upper, middle, and lower reaches. In the SWAT model, the time allocation of IBWT is mainly achieved by regulating the release of water from reservoirs.

The reservoir water balance equation for the reservoir module is as follows:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \tag{2}$$

where V is the water volume of the reservoir at the end of a day; V_{stored} is the water volume stored in the reservoir at the beginning of a day; V_{flowin} is the water volume flowing in the reservoir during one day; $V_{flowout}$ is the water volume flowing out of the reservoir during one day; V_{pcp} is the volume of precipitation falling into the reservoir during one day; V_{evap} is the water volume evaporated from the reservoir during one day; and V_{seep} is the volume of water seepage from the reservoir during one day. The unit of all the variables in the equation is cubic meters.

The use of water resources from IBWT can be divided into three main categories: industrial and domestic consumption, agricultural irrigation, and river runoff increase (Sinha et al. 2020). In the SWAT model, the consumptive water-use management tool was used to simulate industrial and domestic water intake, and the automatic irrigation tool in the subbasin management part was used to simulate irrigation water consumption.

Additionally, SWAT calibration and uncertainty programs (SWAT-CUP) were used to calibrate the parameters in the SWAT model. The performance of the SWAT model was evaluated based on the coefficient of determination (R^2) and Nash–Sutcliffe efficiency (NSE) indicators for the simulation results at a monthly time step.

In this study, based on the measured and natural hydrological data of the Fenhe River basin, the SWAT model based on the natural state and the SWAT model based on the actual state were established. The input data of SWAT model includes spatial data and attribute data. Spatial data include elevation data, land use data and soil data. The digital elevation model data were downloaded from the Geospatial Data Cloud website with a resolution of 30 m (http://www.gscloud.cn). Land use data for 2015 were interpreted from the Landsat 8 OLI dataset. Attribute data includes soil attribute data and meteorological data. Soil attribute data were obtained from the Shanxi soil database and the second national land survey report. Daily meteorological data of five weather stations for the period 1988–2018 were obtained from the China National Meteorological Data Center (http://data.cma.cn/). The monthly subbasin management data were collected from field surveys, and the water quality data of the transferred water were determined based on field samples. Moreover, the monitoring data of the monthly flow, monthly total nitrogen (TN) and total phosphorus (TP) at the Hejin hydrological station from 2010 to 2016 were collected from the Shanxi Academy of Environmental Sciences, China. The models were calibrated with observed data from 2010 to 2013 and validated with data from 2014 to 2016.

2.3 Assessment of Flow Ecological Status

The traditional hydrological Tennant method was used to assess the ecological status of the channels. The Tennant method was first proposed in 1976 and has been applied in many river basins with strong applicability (Li and Kang 2014). In the calculation of the Tennant method, different eco-environmental standards correspond to different flow percentages (Table 1).

Among all the standards, the minimum level is the basic level for maintaining the health of the river ecosystem, and its calculated value of the flow is the target value of the ecological flow. The ecological water shortage refers to the water shortage to achieve ecological flow, and it can be calculated from the difference between the current flow and the target value of river ecological flow (Zhao et al. 2019):

$$E_k = \eta_k \times Q_{natural} \tag{3}$$

$$Q_k = Q_{actual} - E_k \tag{4}$$

Table 1 Ecological flow criteria for the Tennant method (percentages of the average annual flow%)

Ecological flow criterion	Optimum	Outstanding	Excellent	Good	Fair	Minimum
Non-flood season	60~100	40~60	30~40	20~30	10~20	10
Flood season	60~100	50~60	40~50	30~40	20~30	10~20

where η_k represents the flow percentage corresponding to the kth eco-environmental standards; E_1, E_2, E_3, E_4 and E_5 represent the lower bounds of minimum, fair, good, excellent, and outstanding EF (m^3/s), respectively; $Q_{natural}$ represents the average natural flow over long historical periods (m^3/s); Q_K represents the water shortage under the kth ecological environment standard (m^3/s); and Q_{actual} represents the average actual flow over long historical periods (m^3/s).

For the historical natural flow of each channel, the SWAT model based on the natural state of the basin was used to simulate the natural flow in the Fenhe River basin from 1990 to 2018. Furthermore, based on the model established according to the current situation in the Fenhe River basin, the improvement in the status of the river ecological environment with and without the of IBWT projects was analyzed.

For the interannual variability, combined with the average annual measured runoff and the percentage of anomaly, the years from 2010 to 2018 were divided into three hydrological year types: wet, normal, and dry years. The status of satisfying the ecological flow requirement after water diversion was analyzed according to wet, normal, and dry years, and key areas of ecological water shortage were identified.

2.4 Calculation of the Dynamic Water Environment Capacity

The WEC of each channel was calculated by coupling the SWAT model and differential evolution (DE) algorithm (Wang et al. 2019). The DE algorithm is an imitation of biological evolution, which optimizes problems by iteratively trying to improve the candidate solutions related to a given goal (Das and Suganthan 2011). The main calculation processes of the DE algorithm include the initialization of the parameter vectors, mutation with differential operators, and crossover and selection (Storn and Price 1997):

$$\underset{j}{\vec{V}}(t) = \underset{r_1^j}{\vec{X}}(t) + F \cdot (\underset{r_2^j}{\vec{X}}(t) - \underset{r_3^j}{\vec{X}}(t)) \tag{5}$$

where $\underset{j}{\vec{V}}(t)$ is the donor vector; $\underset{r_1^j}{\vec{X}}(t)$, $\underset{r_2^j}{\vec{X}}(t)$, and $\underset{r_3^j}{\vec{X}}(t)$ are randomly picked vectors from the current population; and F is the mutation index defined by the user.

In this study, the target concentrations of phosphorus and nitrogen were set as the objective functions. The goal of the DE algorithm was to allow the final concentration of phosphorus or nitrogen to be as high as possible within the standard concentration limit (Wang et al. 2019). The results of the coupling calculation were the ideal WEC and the remnant WEC of each channel. The ideal WEC is the maximum allowable pollutant capacity, which refers to the maximum amount of pollutants that be discharged to the calculated channel when the upper limit of water quality target was reached. It can be calculated by the equations in QUAL2E (Wang et al. 2019). The remnant WEC was calculated considering the pollutant input from the upstream channels and the corresponding subbasin. The calculation formulas of the remnant WEC are as follows:

$$WEC_{remant} = WEC_{ideal} - Load_{upstream} - Load_{sub} \tag{6}$$

where $WEC_{remnant}$ is the remnant WEC (t/m), WEC_{ideal} is the ideal WEC (t/m), $Load_{upstream}$ is the amount of pollution coming from the upstream channels (t/m), $Load_{sub}$ is the amount of pollution coming from the corresponding subbasin (t/m).

3 Results

3.1 Model Calibration and Validation

In this study, the measured data of Hejin hydrological station were used to calibrate the model, and the calibrated parameters were used for all the 30 subbasins. Based on the sensitivity analysis, 30 parameters were selected to calibrate the flow, and 30 parameters were selected to calibrate the TN and TP concentrations (Table S1 and S2). For monthly flow, the calibration parameters were mainly related to groundwater, soil water and river hydraulic conditions. For monthly total nitrogen and phosphorus, the calibration parameters were mainly related to the physical, chemical and biological cycle of nitrogen and phosphorus. In addition, the SWAT model based on the natural state was calibrated based on the natural flow after reduction, while the SWAT model based on the actual state was calibrated based on measured flow. The calibrated values of parameters for natural flow and measured flow were different. For the SWAT model based on the natural state, the R^2 and NSE values of flow were all greater than 0.7 during the calibration and validation periods (Fig. 2). For the SWAT model based on the actual state, the R^2 of flow, TP, and TN were all greater than 0.6, and the NSE values were all greater than 0.5 during the calibration and validation periods. The errors mainly occurred in the simulation of the dry season, in which the water production process was more complicated due to the influence of human activities such as irrigation and water diversion (Zhang et al. 2015).

3.2 Ecological Status of the Fenhe River Basin without IBWT

According to the simulation results of the SWAT model based on the natural state, the river ecological flow was calculated, and the results showed that the spatial difference was significant (Fig. 3). The ecological flow at the outlet of the downstream was approximately 6 times that of the upstream and twice that of the middle stream. In different hydrological seasons, the spatial distribution characteristics of ecological flow were consistent. For the value of ecological flow, the average ecological water demand of the basin was 74 hm^3/year, and the ecological water demand in the wet season was 10 times that of the dry season. The ratio of environmental requirement refer to the average natural resources was about 40%.

Based on the channel ecological flow, the simulation results of the SWAT model based on the actual state showed that the current flow was larger than the ecological flow in more than 70% of areas, and the difference fluctuated between -0.5–10 m/s (Fig. 4a). Seasonally, the guarantee rate of ecological flow in the dry season (80%) was better than that in the wet season (70%) without the influence of IBWT projects. Spatially, the ecological water shortage mainly occurred in upstream channels 1, 2, and 3 and downstream channels 22, 25, 27, and 29, with the maximum water shortage occurring in channel 29 (-0.5 m/s).

Without the influence of IBWT projects, the spatial distribution of the ideal WEC was similar to that of the river flow, and increased from upstream to downstream, with channels 21, 24, 26, 28, and 30 accounting for about 52% of the total ideal WEC of the basin (Fig. 5a, b). However, different to the status of the ecological flow shortage, the nitrogen and phosphorus pollution status of the Fenhe River basin was much more serious, with the water quality of more than 80% of the total area being substandard. The loads of nitrogen and phosphorous in the downstream were the largest (Fig. S1). The remnant WEC results showed that TN pollution was more serious than TP pollution, and that TP and TN showed

Fig. 2 Calibration and validation results of SWAT models (**a**: flow of SWAT model based on the natural state; **b**: flow of SWAT model based on the actual state; **c**: TN of SWAT model based on the actual state; d: TP of SWAT model based on the actual state)

different seasonal variations. The negative values of remnant WEC means that the current pollutant discharge has exceeded the water quality standard of the river, and the values are the amount of pollution that needs to be reduced. The remnant WEC of TN was negative in all channels, and the lowest values appeared in the midstream and downstream channels over the entire year, while the spatial variation of the remnant WEC of TP was more affected by seasonal changes (Fig. 6a, b). In the dry season, more than 80% of channels had negative values for the remnant WEC of TP, and the midstream and downstream channels were the most polluted areas, with a minimum value of -3 t/m. In the wet season, negative values of the remnant WEC mainly appeared in 30% of upstream channels, with a minimum value of -5 t/m.

The monthly variation of the ideal WEC were analyzed based on the average of the WEC for all channels of the basin. The monthly variation trends of the ideal WECs of TN and TP were the same, and the maximum ideal WEC appeared in October, which was approximately 10 times the minimum ideal WEC in March (Fig. 7a, b). However, the remnant WEC of TN was quite different from that of TP. Except for November, all monthly remnant WEC values of TN in the dry season were larger than those in the wet season. While, more than 65% negative values of monthly remnant WEC of TP occurred in the dry season. For TN, the largest remnant WEC was found in January, which was 750 t/m higher than the minimum value in July. For TP, the largest remnant WEC occurred in September, which was 8 t/m higher than the minimum value in April.

3.3 Effects of IBWT Projects on the Flow Ecological Status

According to the simulation results of the SWAT model based on the actual state with IBWT, the river flow increased by 36% across the basin, and the increase in river flow in the dry season (80%) was much higher than that in the wet season (20%) (Figs. 8 and S2). The flow changes of each channel showed that the inclusion of IBWT projects effectively improved the flow velocity of 63% of channels, especially during the dry season (Fig. 8a, b). Among them, approximately 50% of channels showed an improvement in the flow ecological status in the dry season, while the improvement rate in the wet season was 33%.

However, although IBWT significantly increased the mainstream flow, approximately 23% of channels did not meet the ecological flow requirement when IBWT projects were included in the model, especially channels 1, 25, and 27 (Fig. 4b–d). Combined with the analysis of different hydrological years, channels 1, 25, and 27 had the highest probability of ecological water shortage, with values up to 85%. Additionally, the distribution of ecological water shortage areas changed under different hydrological year types. In the dry season, the channels experiencing water shortage in different hydrological years were consistent with the high frequency water shortage areas, except for channel 11. In the wet season, channels 7, 8, 11, and 29 became new water shortage areas in the normal and dry years, and the assured rates of ecological flow for the wet season in wet, normal, and dry years were 93%, 90% and 77%, respectively.

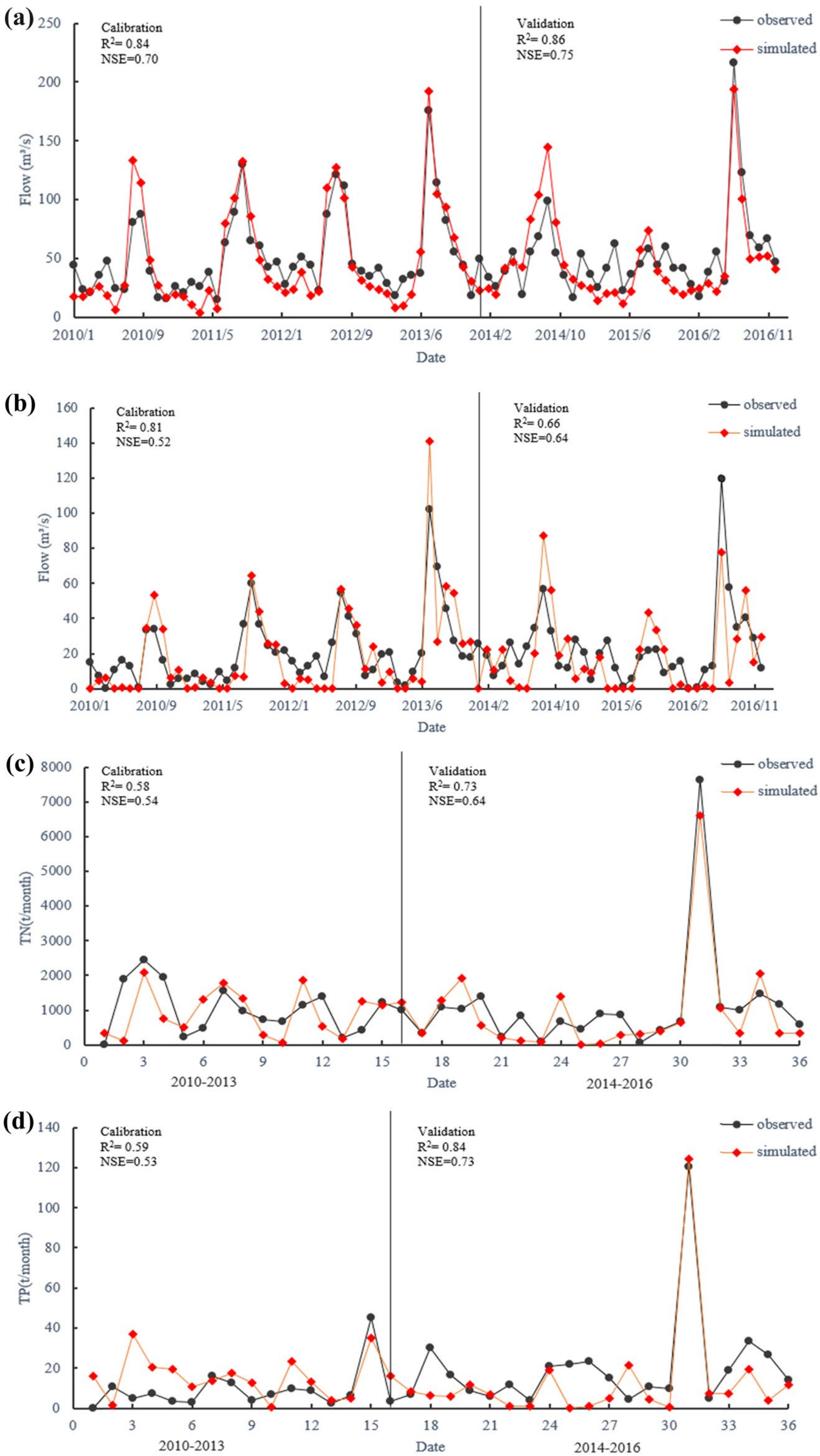
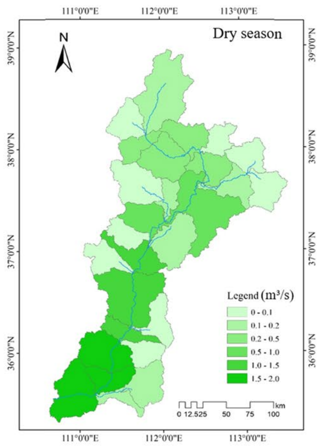
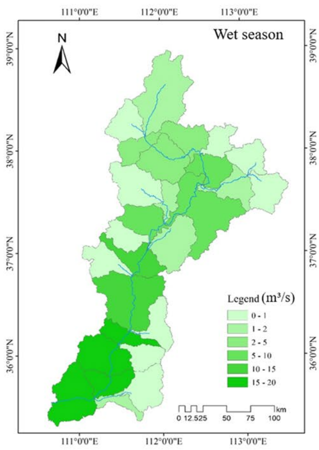

(a)
Calibration
R^2= 0.84
NSE=0.70
Validation
R^2= 0.86
NSE=0.75
observed
simulated
Flow (m³/s)
0
50
100
150
200
250
2010/1
2010/9
2011/5
2012/1
2012/9
2013/6
2014/2
2014/10
2015/6
2016/2
2016/11
Date
(b)
Calibration
R^2= 0.81
NSE=0.52
Validation
R^2= 0.66
NSE=0.64
observed
simulated
Flow (m³/s)
0
20
40
60
80
100
120
140
160
2010/1
2010/9
2011/5
2012/1
2012/9
2013/6
2014/2
2014/10
2015/6
2016/2
2016/11
Date
(c)
Calibration
R^2= 0.58
NSE=0.54
Validation
R^2= 0.73
NSE=0.64
observed
simulated
TN(t/month)
0
1000
2000
3000
4000
5000
6000
7000
8000
0
3
6
9
12
15
18
21
24
27
30
33
36
2010-2013
Date
2014-2016
(d)
Calibration
R^2= 0.59
NSE=0.53
Validation
R^2= 0.84
NSE=0.73
observed
simulated
TP(t/month)
0
20
40
60
80
100
120
140
0
3
6
9
12
15
18
21
24
27
30
33
36
2010-2013
Date
2014-2016

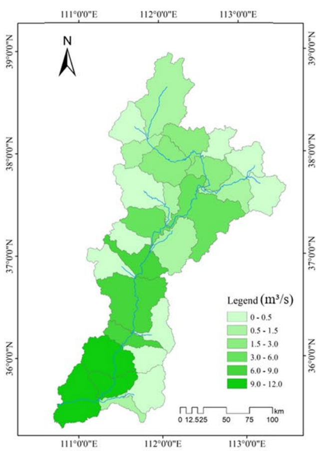
Fig. 3 Spatial distribution of ecological flow and ecological water demand (**a**: ecological flow in dry season; **b**: ecological flow in wet season c: ecological water demand)



(a)



(b)



(c)

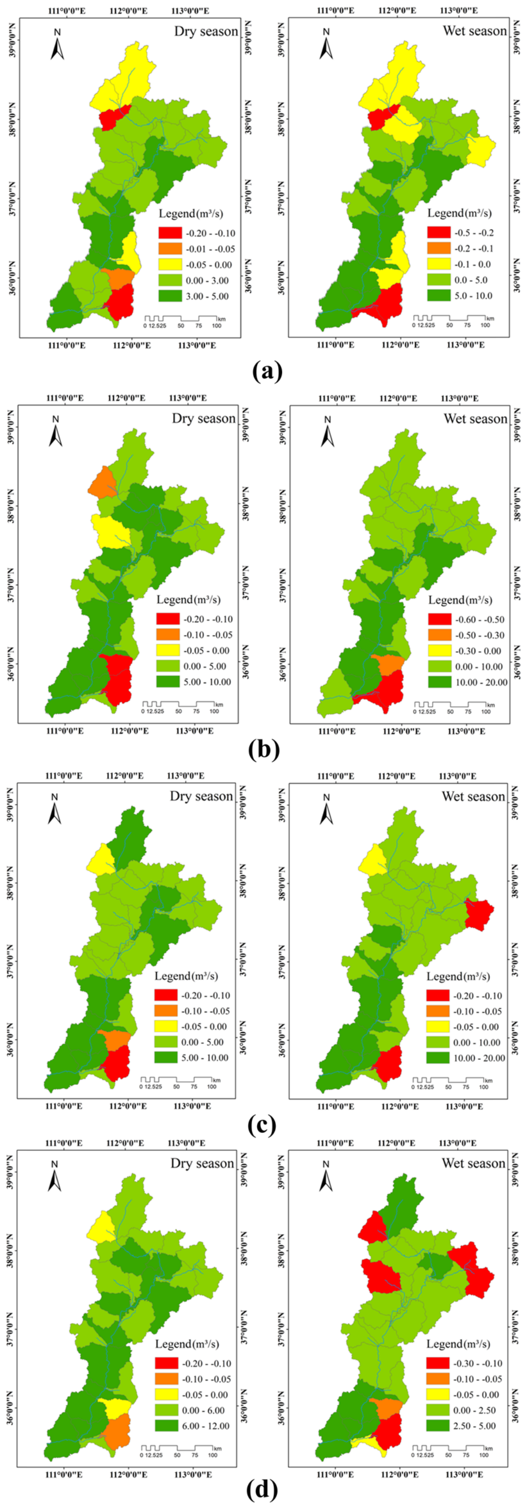


Fig. 4 Spatial distribution of ecological water shortage: (**a**) Without IBWT projects; (**b**) Wet years with IBWT; (**c**) Normal years with IBWT; (**d**) Dry years with IBWT

Fig. 5 Spatial distribution of the ideal WEC: (**a**) TN ideal WEC without IBWT; (**b**) TP ideal WEC without ▸ IBWT; (**c**) TN ideal WEC with IBWT; (**d**) TP ideal WEC with IBWT

3.4 Effects of IBWT Projects on the Dynamic Water Environment Capacity

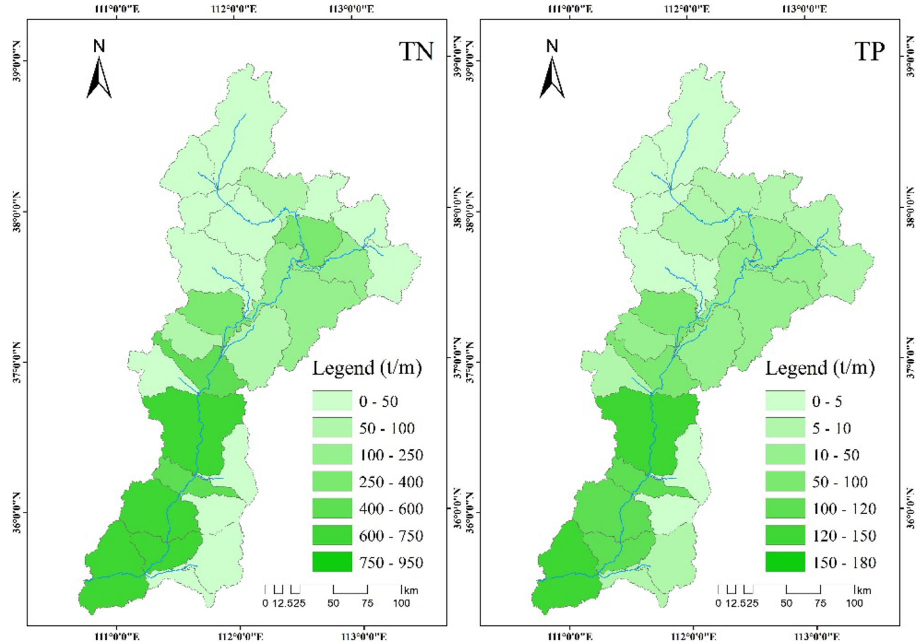
Affected by IBWT, the ideal WECs of TN and TP increased by 48% across the basin, with upstream and downstream channels being the main contributors to this increase (Fig. 5c, d). Among them, the increment of channel 24 was the largest, accounting for approximately 10% of the total increment of the basin. However, the change in the remnant WEC was different from the change in the ideal WEC. The results of the annual remnant WEC showed that the remnant WECs of TN and TP decreased in approximately 20% and 44% of channels, respectively (Fig. 9). Moreover, the spatial variation trends of the remnant WEC were opposite for TN and TP. The remnant WEC of TN mainly increased in the midstream and downstream regions, with an average increase of approximately 1.5%. In contrast, the remnant WEC of TP mainly increased in the upstream region, with an average increase of approximately 300%.

Additionally, IBWT projects had opposite seasonal effects on the remnant WECs of TN and TP (Fig. 6c, d). In the dry season, the remnant WEC of TN decreased by 2% after IBWT, while the remnant WEC of TP increased by 140%. In the wet season, the remnant WEC of TN increased by 4%, while the remnant WEC of TP decreased by 80%. Spatially, in the dry season, the largest changes in the remnant WECs of TN and TP occurred in channels 2 and 4, respectively, while the largest changes in both remnant WECs occurred in channel 22 in the wet season.

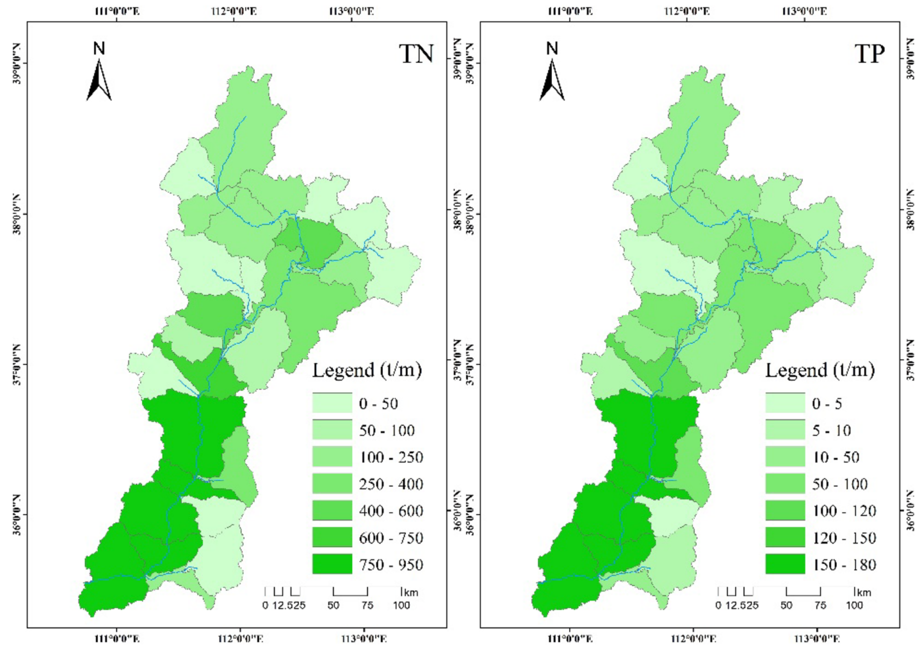
The monthly variation trends of the ideal WECs of TN and TP were the same, and increased each month after IBWT (Fig. 7c, d). The largest ideal WEC increment occurred in March, which was approximately 8 times the minimum increment in February. However, the monthly variation in the subbasin load was significantly different for TN and TP. After IBWT, the subbasin load of TN increased by 10% in the dry season and decreased by 3% in the wet season, while the subbasin load of TP increased in each month with an average increase of 40%. Meanwhile, affected by both the ideal WEC and subbasin load, the remnant WEC showed different changes for TN and TP in the same month. The remnant WEC of TN decreased on average by 30 t/m from January to April and increased on average by 24 t/m from May to December, while the remnant WEC of TP decreased on average by 1.3 t/m from July to October and increased on average by 1.1 t/m in other months of the year.

4 Discussion

In this study, the SWAT model was used to perform multi-simulations of the Fenhe River basin to quantify the channel flow and water quality with and without IBWT. The model simulation improved the accuracy of the impact analysis by maintaining the consistency of the hydrological conditions in the evaluation process (Wang et al. 2016). However, based on simplified hydrological models, many previous studies quantifying the effects of IBWT projects ignored the dynamic changes in the real hydrological and meteorological environments, which may result in inaccurate results (Nikoo et al. 2012; Wang et al. 2016). As a typical semi-distributed hydrological model, the SWAT model can output results at daily, monthly, and annual timescales, thus ensuring the dynamic change of the results under the actual hydro-meteorological environment (Teshager et al. 2017).


TN
TP
N
Legend (t/m)
0 - 50
50 - 100
100 - 250
250 - 400
400 - 600
600 - 750
750 - 950
0 - 5
5 - 10
10 - 50
50 - 100
100 - 120
120 - 150
150 - 180
0 12.525 50 75 100 km
111°0'0"E
112°0'0"E
113°0'0"E
39°0'0"N
38°0'0"N
37°0'0"N
36°0'0"N

(a)


TN
TP
N
Legend (t/m)
0 - 50
50 - 100
100 - 250
250 - 400
400 - 600
600 - 750
750 - 950
0 - 5
5 - 10
10 - 50
50 - 100
100 - 120
120 - 150
150 - 180
0 12.525 50 75 100 km
111°0'0"E
112°0'0"E
113°0'0"E
39°0'0"N
38°0'0"N
37°0'0"N
36°0'0"N

(b)

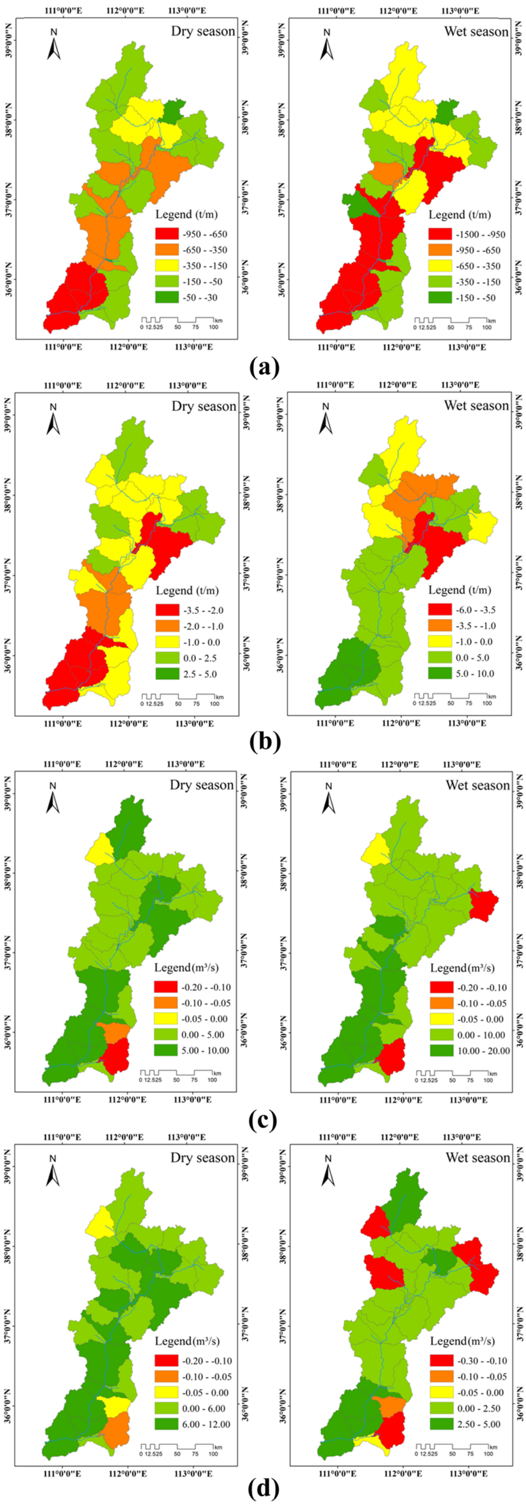


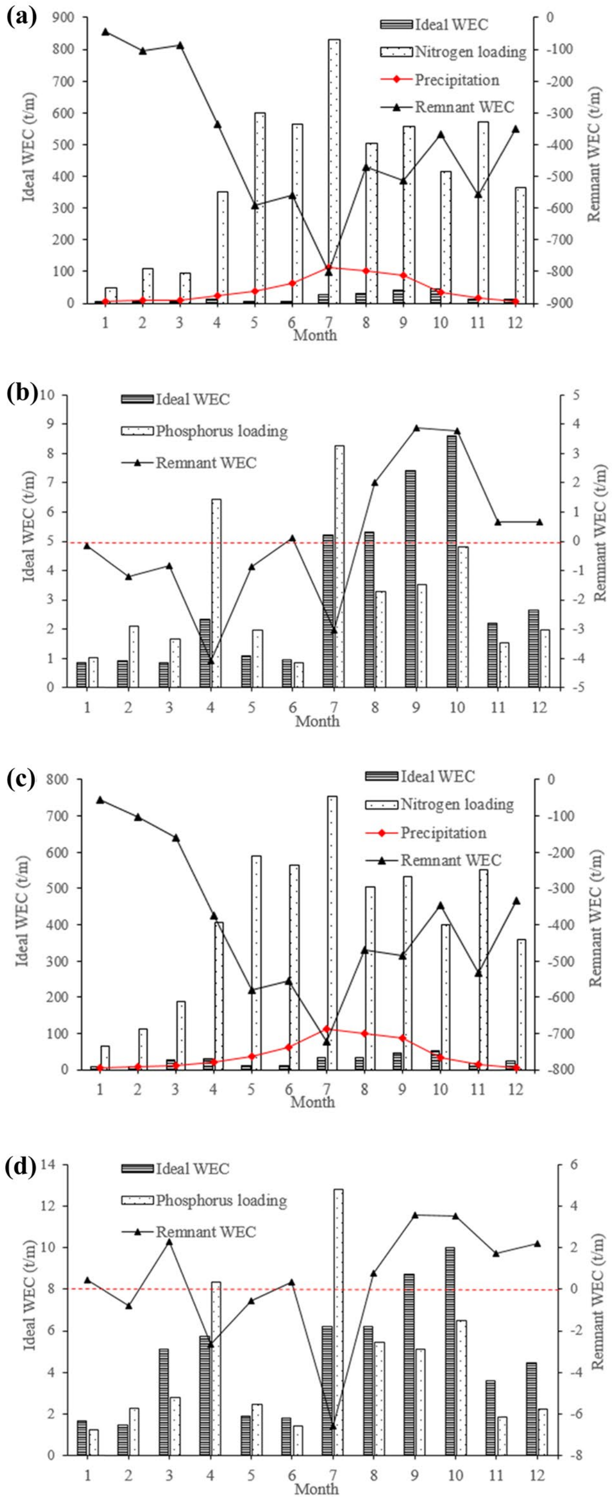
Fig. 6 Spatial distribution of the remnant WEC: (**a**) TN remnant WEC without IBWT; (**b**) TP remnant WEC without IBWT; (**c**) TN remnant WEC with IBWT; (**d**) TP remnant WEC with IBWT

In the Fenhe River basin, the water resource crisis is characterized by the coexistence of water shortage and water pollution (Li et al. 2020). The overall impact of IBWT projects has been the significantly improvement in the channel water volume and water quality. Under the existing IBWT projects, approximately 380 million tons of water were imported into the study area each year from 2010 to 2018, which significantly increased the channel runoff of the mainstream and improved the eco-environmental status of the flow (Yuan et al. 2018). Such an increase in water volume can effectively alleviate the problem of water shortage (Karandish et al. 2021; Sun et al. 2021). Additionally, the WEC increased when IBWT projects were included in the model because the increased water volume of channels led to an increased dilution capacity (Wang et al. 2019). Studies have shown that by increasing the river flow velocity and dissolved oxygen concentration, IBWT projects can also increase the self-purification capacity of a river (Sadef et al. 2014).

In this study, the spatial distribution of the impact of IBWT on each channel was not uniform because of the limited water diversion points. For channel flow, the changes were mainly concentrated in the mainstream, and the impacts gradually decreased toward the downstream direction (Woo et al. 2021). For the WECs of different channels, the changes were affected by the pollution concentrations of the transferred water and water quality targets of recipient channels (Nikoo et al. 2012). In Fenhe River basin, all nutrients and sediments from the donor reservoirs were transferred to the receiving area without purification in IBWT projects. The pollution concentrations difference between transferred water and the water quality target of water-receiving basin can change the dilution capacity of a channel (Hu et al. 2010). Under the same quality of transferred water, the IBWT projects showed different impacts on the WECs of upstream and downstream channels, which may be related to the spatial differences in the water quality targets of recipient channels. According to the surface water function zoning of Shanxi Province, the water quality targets of channels are different under different development and utilization functional zones (Wang and Xie 2014).

The monthly changes caused by IBWT projects were related to reservoir discharge, precipitation, and non-point source pollution in the basin. The Fenhe River basin has a temperate continental monsoon climate, with 70% of the annual precipitation concentrated in the summer (Sun et al. 2020). Reservoir discharge in the dry season exceeds that in the wet season; hence, the increase in flow is more significant in the dry season (Yuan et al. 2018). With the significant increase in channel flow in the dry season, the increase in the ideal WEC in the dry season was higher than that in the wet season because of the dilution capacity (Wang et al. 2019). However, the increment in the ideal WEC caused by the unit water transfer volume was higher in the wet season, which might be because the degradation coefficients of pollutants increase at higher temperatures (Borah et al. 2006).

The impacts of IBWT projects on the remnant WECs of TN and TP were different. Non-point source pollution is an important source of TN and TP, with fertilization and soil nutrient loss having the highest contribution rates (Li et al. 2020). The loads of TN and TP in the channels showed different rates of increase with surface runoff because of the different levels of fertilizer use and soil nutrient contents (Huang et al. 2017). In the Fenhe River basin, IBWT projects mainly supply water for agricultural irrigation in the middle and lower reaches, accounting for more than 50% of the transferred water resources (Zhang and Guo 2016). Under the IBWT projects, the surface runoff was enhanced, which caused different pollution load increases for TN and TP. On the other hand, the remnant WEC was also affected by the dilution capacity and self-purification capacity (Wang et al. 2019). For the dilution capacity, the different TN and TP concentrations of the transferred water led to different changes in the dilution capacities of each channel. For the self-purification capacity, the


(a)
Ideal WEC
Nitrogen loading
Precipitation
Remnant WEC
Ideal WEC (t/m)
Remnant WEC (t/m)
Month
(b)
Ideal WEC
Phosphorus loading
Remnant WEC
Ideal WEC (t/m)
Remnant WEC (t/m)
Month
(c)
Ideal WEC
Nitrogen loading
Precipitation
Remnant WEC
Ideal WEC (t/m)
Remnant WEC (t/m)
Month
(d)
Ideal WEC
Phosphorus loading
Remnant WEC
Ideal WEC (t/m)
Remnant WEC (t/m)
Month

◀**Fig. 7** Monthly variations of the ideal WEC, the remnant WEC and load input: (**a**) TN without IBWT; (**b**) TP without IBWT; (**c**) TN with IBWT; (**d**) TP with IBWT

IBWT projects affected the pollutant degradation rate by changing the channel flow velocity and dissolved oxygen concentration, which resulted in different self-purification increments of TN and TP (Wang et al. 2016).

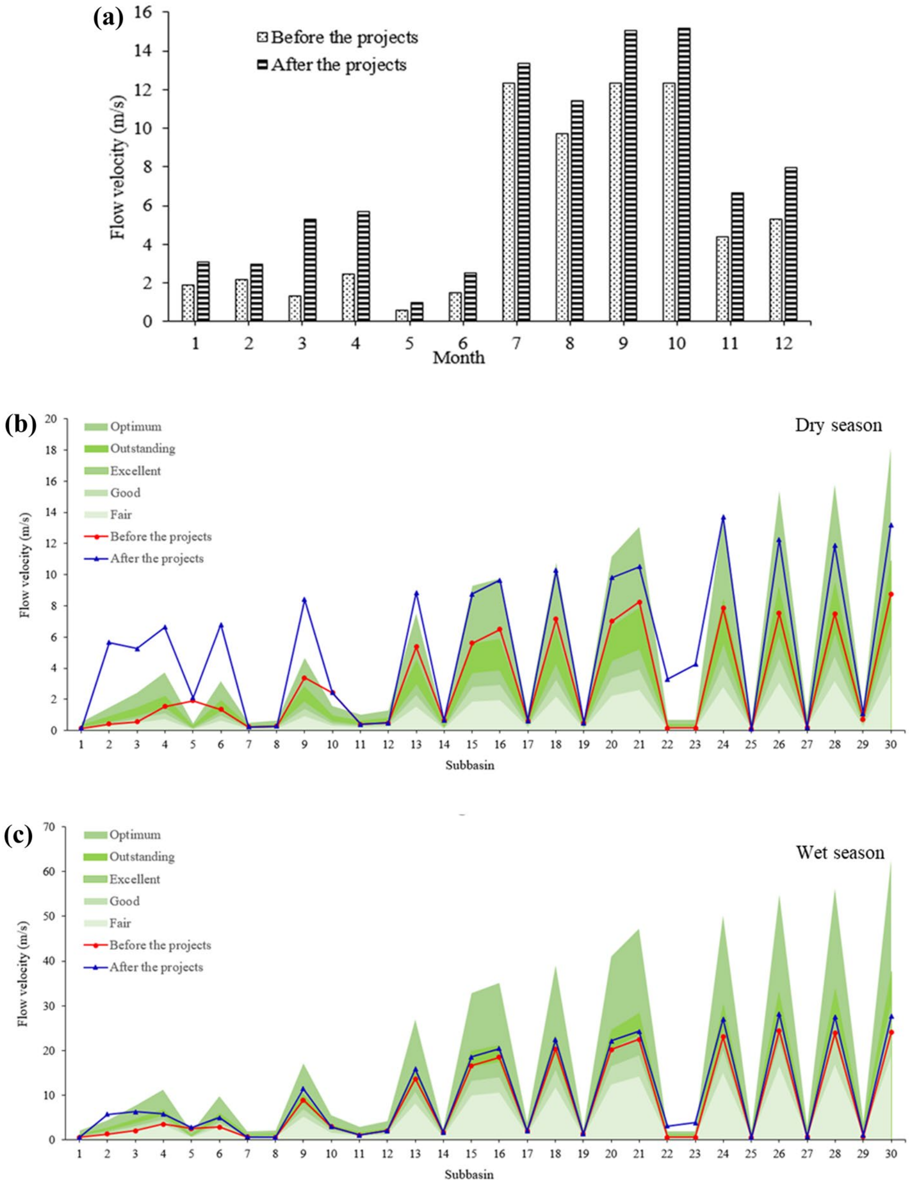


Fig. 8 Changes of flow velocity before and after IBWT projects: (**a**) Monthly variation; (**b**) Flow of channels in dry season; (**c**) Flow of channels in wet season

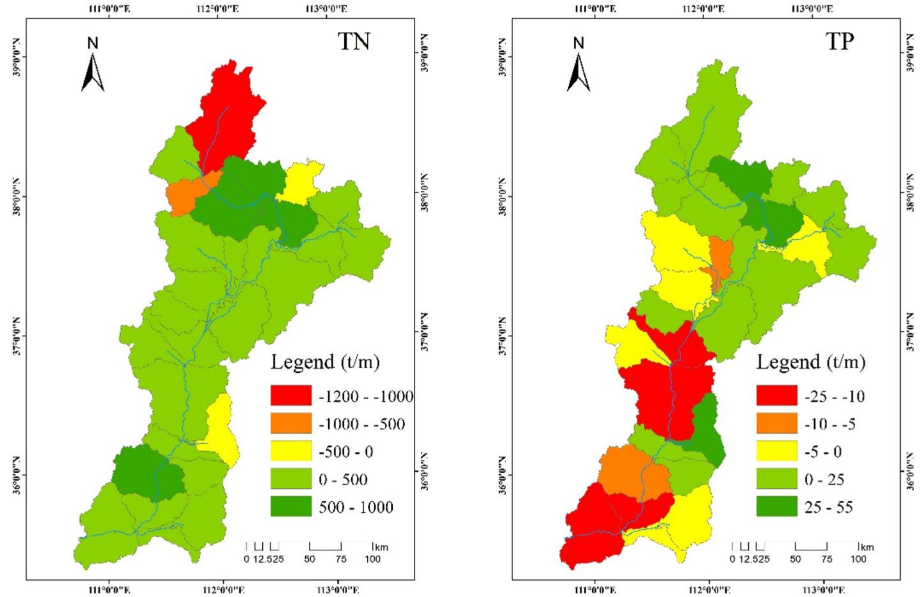


Fig. 9 Spatial variation of the annual remnant WEC with or without IBWT

During the operation of IBWT projects, the temporal and spatial impacts of IBWT exhibited dynamic changes in the river basin (Fig. 8). In hydrological systems, uncertainties caused by random changes in the environment exist widely (Song et al. 2011). Affected by precipitation, the ecological conditions of channel flow and non-point source loadings changed considerably, which caused high randomness in the impact analysis of IBWT. To ensure the reliability of the results, more attention should be paid to the dynamic impact of IBWT projects on channels to establish long-term hydrological models of IBWT projects (Rogers et al. 2020; Woo et al. 2021). Furthermore, quantifying the spatiotemporal impacts of IBWT projects based on the dynamic hydrological processes of a basin could provide effective guidance for management after the construction of IBWT projects (Gu et al. 2017).

5 Conclusions

An IBWT project can alleviate the uneven distribution of water resources in time and space, and not only meet the increasing demand for water, but also maintain the ecosystem health of watersheds. In this study, the SWAT model was used to simulate and quantify the average monthly flow and WEC of channels in the Fenhe River basin with or without IBWT projects, and evaluate the spatiotemporal changes in the impacts of IBWT. Without the influence of IBWT, the current flow was larger than the ecological flow in more than 70% of areas, and the guaranteed rate of ecological flow in the dry season (80%) was better than that in the wet season (70%). However, different with the status of the ecological flow shortage, the nitrogen and phosphorus pollution of the Fenhe River basin was much more serious, with more than 80% of the basin characterized by a substandard water quality.

Under the IBWT projects, approximately 63% of the channels experienced a significant increase in flow, and the increase in the dry season (80%) was much higher than that in the wet season (20%). However, although IBWT significantly increased the mainstream flow, approximately 23% of channels did not meet the ecological flow requirement under the IBWT projects. Hence, more attention should be given to key water-deficient areas and a more reasonable spatial allocation of water resources should be made.

The changes in the ideal WEC were positively correlated with channel flow, with an average increase of 48% across the basin. However, the change in the remnant WEC was affected by the pollution load changes. Although the remnant WECs of TN and TP increased in most parts of the basin, they decreased in approximately 20% and 44% of channels, respectively. Moreover, the IBWT projects had different seasonal effects on the remnant WECs of TN and TP. In the dry season, the remnant WEC of TN decreased by 2% after IBWT, while the remnant WEC of TP increased by 140%. In the wet season, the remnant WEC of TN increased by 4%, while the remnant WEC of TP decreased by 80%. To improve the ecological environment of the water-receiving basin, the potential pollution load associated with IBWT projects should be considered carefully.

In summary, because of the random changes in the hydrological environment, the temporal and spatial characteristics of the impacts of IBWT projects exhibited dynamic changes in the Fenhe River basin. The long-term simulation of IBWT projects in the SWAT model not only improved the reliability of the results, but could also provide effective guidance for management after the construction of IBWT projects.

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Authors Contributions LiJun Jiao: Conceptualization, Methodology, Software, Writing - Original Draft. Ruimin Liu: Conceptualization, Writing - Review & Editing, Funding acquisition. Linfang Wang: Data curation, Software, Validation. Lin Li: Visualization, Investigation. Leiping Cao: Resources, Investigation.

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Availability of Data and Materials The total data and materials are available for applicants if needed.

Declarations

Ethical Approval The authors approve principles of ethical and professional conduct.

Consent to Participate The authors consent to participate in the preparation of this article.

Consent to Publish The authors consent to publish this article in journal of Water Resources Management.

Competing Interests There is no conflict of interest.

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