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Quantification of sector-specific groundwater withdrawals considering water diversion projects in the Hebei Province, China

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ABSTRACT

Study area: Hebei Province, China
Study focus: Accurate assessment of sector-specific groundwater withdrawals (GWW) is fundamental for targeted groundwater management policies, particularly in regions suffering from severe groundwater over-extraction. Due to the lack of statistical data and the coarse resolution of water supply patterns and GWW, previous studies couldn't well quantify the GWW where the impact of inter-basin water diversion projects was also neglected. Here we proposed a methodology to simulate sectoral GWW based on flux balance in consideration of the influence of inter-basin water diversion projects.
New hydrological insights for the study region: A case study in Hebei Province, where groundwater is severely over extracted, was used to validate our methodology. Our results showed that the gridded GWW calculations are well aligned with the statistical data from the Hebei Water Resources Bulletin (WRB) at both provincial and municipal levels, with correlation coefficients (R) above 0.9 and normalized root mean squared errors (NRMSE) below 0.1. County-level GWW estimates also match with data from the Department of Water Resources of Hebei Province for 2013 and 2018, with NRMSE around 0.2. Piecewise Linear Regression (PLR) analysis of sectoral GWW further reveals that GWW is quickly declined when water diversion projects or policies are implemented. Together our findings underscore a significant role of water resource engineering and policies in alleviating groundwater over-extraction.

1. Introduction

Groundwater is one major source of freshwater that supports our ecosystems and livelihoods (Muenratch et al., 2022; Margat and Gun, 2013). Over extraction of groundwater can result in the decline of groundwater levels followed by a series of geologic hazards

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such as seawater intrusion, land subsidence, streamflow depletion and wells running dry (Jasechko et al., 2024) while human activities on water resources could significantly impact the evolving water supply patterns. Accurate assessment of sub-sectoral GWW is critical for making targeted groundwater management policies, particularly in regions facing severe groundwater over-extraction. GWW varying among the sectors with disparities in water demands, distribution patterns, and associated anthropogenic factors. Approximately 70 % of global extracted groundwater are allocated for agricultural purposes (Long et al., 2020; Margat and Gun, 2013). High water-consumption but lower water recycling in the agricultural sector result in the increase in disparities in water demands among sectors.

Moreover, depending on where the extracted groundwater ends up, the impacts of different sectoral GWW on groundwater resources are different (Sun et al., 2022). Long et al. (2020) demonstrated the critical importance of water sources for different water use sectors. They highlighted the interactions and constraints of different water sources within various water use scenarios, such as in agricultural irrigation, where the loss of surface water resources can be compensated by the recharge of groundwater resources. Other studies also illustrated that agricultural irrigation withdrawals would help recharge groundwater by effectively replenishing aquifers (Scanlon et al., 2023; MacAllister et al., 2022). In contrast, domestic and industrial GWW ultimately flow into surface-water systems and deplete the groundwater. Besides, human interventions on groundwater resources impact the evolving water use patterns. For instance, domestic and ecological water demands increases as a result of higher population density and increased environmental protection, while decreasing in industrial and agricultural water demands can be attributed to the adoption of technologies that promote industrial water conservation and the implementation of policies, such as restrictions on groundwater extraction (Department of Water Resources of Hebei Province, 2022; Zhou et al., 2020). Therefore, understanding of the sectoral GWW would be fundamental for making sector-specific groundwater management policies.

In addition to the intrinsic nature of GWW mentioned above, inter-basin water diversion projects have significant impact on groundwater resources in many aspects. First, the diverted water replaces groundwater resources in various sectors of the receiving area, resulting in a reduction in groundwater extraction. For instance, diverted water increased while the proportion of groundwater supply decreased from 66 % to 42 % in Haihe River Basin between 2000 and 2019 (Long et al., 2023). Second, diverted water is extensively utilized for ecological replenishment of rivers and lakes, which restores the surface water ecosystems, replenishes the aquifers and mitigates the excessive exploitation of groundwater. Quantifying each sector's GWW becomes particularly important to comprehensively understand how water supply pattern changes influence groundwater dynamics and the mechanism behind (Yang et al., 2022; Long et al., 2020 ; Zhang et al., 2020).

Previous studies have limitations in quantification of sectoral GWW due to the lack of data and the coarse resolution of the water supply patterns and GWW. First, the data was not available over a wide area. In China, most of the provinces have only the total groundwater extraction and sector-specific water withdrawals data, and public statistical data on basin-scale and municipal-scale sector-specific GWW is only available in Gansu Province. Second, some studies though have proposed methods for calculating water supply and use, they focused on water consumption by sector and surface water and groundwater withdrawals, without conducting analyses that integrate both sectoral and source-specific perspectives (Pokhrel et al., 2015; Wada et al., 2014; Huang et al., 2023). The significant impacts of water diversion projects (Huang et al., 2023; Huang et al., 2018; Ma et al., 2020) were neglected as well. Besides, the latest WaterGAP 2.2d model can compute groundwater withdrawal proportions for different sectors (Müller Schmied et al., 2021), while the values are multi-year average which cannot reflects the temporal changes in the dependency of various sectors on water resources due to human activities. Furthermore, the model assumes that groundwater resources are infinitely available when calculating groundwater withdrawal proportions, which is not consistent with the actual situation. Zeng et al. (2016) successfully simulated the impact of human activities on groundwater dynamics using municipal-level sectoral GWW data from Gansu Province's Water Resources Bulletin. However, due to the strong spatial heterogeneity of aquifers, it is challenging to accurately depict the spatial distribution of groundwater resources in response to exploitation behaviors solely based on municipal-level data. The absence of sector-specific GWW time series and the low spatial resolution limit our ability to quantify changes in the water supply pattern and simulations of the impacts on groundwater resources. Therefore, there is an urgent need to develop a comprehensive computational methodology to address these data deficiencies.

The region of interest in this study is Hebei Province, China. This area as selected was case study for three reasons. First, Hebei Province constitutes a significant part of the North China Plain (NCP), characterized as the most complex region in water composition, severe water-deficient with challenges in water resource allocation in the NCP. Second, the primary water source in Hebei Province is groundwater, accounting for approximately 70 % of the total water supply. Since the late 1970s, groundwater extraction has been continuously increased. Prolonged and severe over-extraction of groundwater led to a large-scale groundwater depression cone in Hebei. Consequently, it triggered a series of environmental geological issues, including land subsidence, ground fissures, wetland degradation, and seawater intrusion, all of which impede sustainable socioeconomic development (Shi et al., 2014). To alleviate the over-exploitation of groundwater, Hebei government has implemented a series of policies to save water and restore groundwater level since 2014. Third, the water supply pattern in Hebei has been significantly changed since 2000, especially after the operation of inter-basin water diversion projects and the implementation of groundwater management policies. Two significant inter-basin water diversion projects transporting diverted water to Hebei Province called the South-to-North Water Diversion Project (SNWD) and Yellow River Diversion Project (YRD). The SNWD and the YRD have provided Hebei Province with substantial diverted water as a substitution of groundwater, which significantly influenced the water supply pattern in Hebei. Completed in 1993, the YRWD plays a vital role in agricultural irrigation and ecological replenishment for Baiyangdian Wetland in Hebei Province. The Middle Route of the SNWD (SNWD-M), operational since the end of 2014, provides crucial water supply to the domestic, industrial, and ecological sectors in Hebei Province. In recent years, due to the climate change, population growth, and rapid economic development, water demands increased and situation is getting worse in Hebei Province. Precise estimation of sector-specific GWW in Hebei Province is important for making targeted groundwater management policies.

In this study, we developed a flux-based methodology that combines data of inter-basin water diversion projects in consideration of the priorities of sector-specific water supply and calculated the sector-specific GWW data. The method of our study is based on Huang et al. (2023), the actual withdrawals of surface water and groundwater is calculated through a flux-based model and upstream and downstream hydrological relationship. Among them, the calculation of environmental flow is based on VMF method mentioned in Veldkamp et al. (2017). In addition, according to the proportion of flood discharge in flood season to surface water resources in the basin of Hebei Province, the unavailable flood quantity is excluded from the surface water resources to reduce the overestimation of the surface water availability (Zhou et al., 2020). The contribution of the study is the first time to present the water-supply priorities across different sectors based on the established policies and relevant literature in Hebei Province. Therefore, we can further quantify the allocation of source-specific water (i.e., surface water, groundwater, and other water withdrawals) to each water use sectors (i.e., agricultural, domestic, industrial, and environmental water use sector) (Fig. 3). Our results showed that the methodology could accurately quantify human water consumption and assess the impact of water supply pattern on groundwater resources, which would be useful for global water resource management research in the future.

2. Study area and data

This study selected Hebei Province, China as study area. Hebei Province is situated between 36°05′ to 42°40′ N latitude and 113°27′ to 119°50′ E longitude, with a total area of 188,000 square kilometers (Fig. 1). It is composed of 11 cities and 167 counties. Hebei is located in the north of the North China Plain, bounded by the Yanshan and Taihang Mountains on the north and west sides, bordered by the Bohai Sea on the east, and connected with the Yellow River alluvial Plain and the Luxi Plain on the south (Zhang, 1961). The terrain falls from northwest to southeast. Among the dominant land cover types as cropland, woodland, shrub, and construction land, crop land accounts for the largest proportion (Wang et al., 2022). Hydrogeological structure of the region gradually changed from the single thick coarse-grained aquifer in front of Yanshan and Taihang Mountains to the multi-layer fine-grained aquifer in the middle and eastern part of the plain (Duan and Xiao, 2003). Based on the lithology and hydrogeological conditions of the sediments, the Hebei

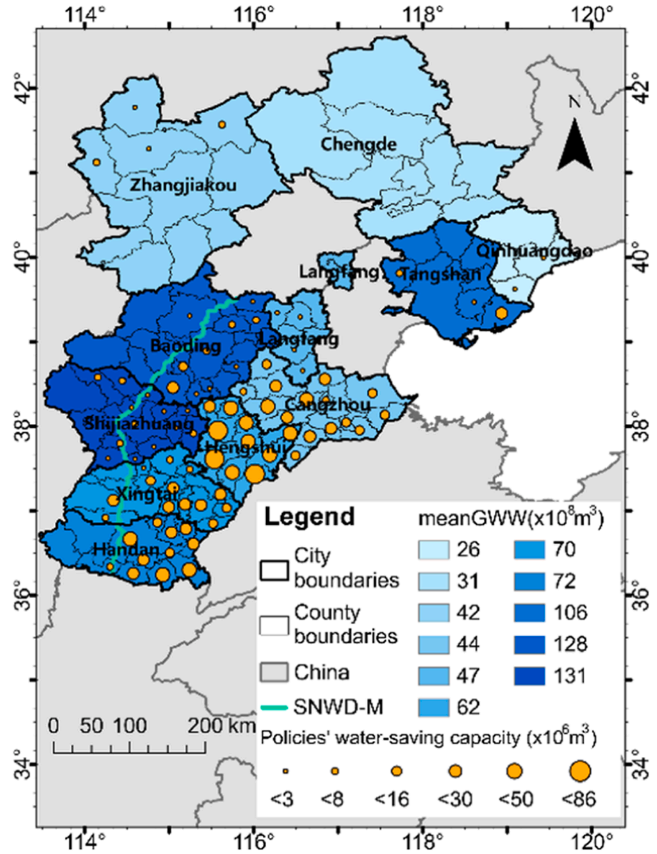

Fig. 1. Map of the study area, Hebei Province in China. The gradual blue color indicates the average annual GWW of each city in Hebei Province from 2000 to 2021, and the darker the color, the more water withdrawn, and vice versa. The bright green solid line depicts the route of South-to-North Water Diversion Middle route (SNWD-M) in Hebei Province. The orange pie chart shows the water-saving capacity of the policies implemented in Hebei Province.

Plain can be vertically divided into four aquifers, of which the uppermost aquifer is shallow aquifer and the rest are called confined aquifer (Tang et al., 2023). Hebei Province has a temperate continental monsoon climate with four distinct seasons. The average annual precipitation is 400–600 mm, and is more in southeast and less in northwest.

In recent years, due to the climate change, population growth, and rapid economic development, water demands increased and situation is getting worse in Hebei Province. Precise estimation of sector-specific GWW in Hebei Province is important for making targeted groundwater management policies. Using our proposed methodology, we estimated that the total groundwater extraction is at 2 km×2 km grid scale and sectoral GWW at the county level of Hebei Province during 2000–2018. Specific datasets and descriptions are shown in Table 1.

3. Methods

Our study aims to obtain county-scale sector-specific GWW in Hebei Province, while the source input data such as sectoral water demands, source-specific water withdrawals, and diverted water are provincial or municipal scale. Therefore, we first downscaled the provincial and municipal data into network scale and calculated the total GWW based on flux-balance method in gridded scale (Fig. 2). Considering the water-supply priority (Fig. 3) is rather applicable in administrative scale as county-level than fine gridded scale, we then upscaled our gridded results into county-level and allocated the identical water sources to each sector according to the assumed water-supply priority based on established policies and relevant literature.

3.1. Sectoral water demands

To calculate gridded sectoral water demands (i.e., sectoral water use in this study), administrative-scale sectoral water withdrawals was first obtained from the provincial/municipal WRB and then downscaled to grid scale following previous studies (Zeng et al., 2018; Huang et al., 2018; Ma et al., 2020). Agricultural water demands, industrial water demands and domestic water demands were downscaled based on the gridded effective irrigation area (Eq. 1), gross domestic product (GDP) (Eq. 2) and population density map (Eq. 3), respectively. The environmental water demands including urban public water demands and ecological water demands for recharging rivers, lakes and wetlands were downscaled respectively by the impervious layer area (Eq. 4) and water area (Eq.5)

Table 1
Data required for water resource allocation model simulation in Hebei Province.

Parameters	Description	Data sources	Resolution
Q_{sw}	Surface water availability	Hebei Water Resources Bulletin (Department of Water Resources of Hebei Province, 2000–2018)	2000–2009, Provincial level. 2010–2018, Municipal level
$Q_{su,report}$	Surface water withdrawals		
$Q_{gu,report}$	Groundwater withdrawals		
Q_{agr}	Agricultural water demands		
Q_{dom}	Domestic water demands		
Q_{ind}	Industrial water demands		
Q_{env}	Environmental water demands		
$R_{agr,con}$	Agricultural water consumption rate		
$R_{dom,con}$	Domestic water consumption rate		
$R_{ind,con}$	Industrial water consumption rate		
$R_{env,con}$	Environmental water consumption rate		
Q_{dw}	Volume of water from South-to-North Water Diversion Project/Yellow River Diversion Project		2000–2018, Provincial level
GWW_{agr}	Agricultural groundwater withdrawals	Department of Water Resources of Hebei Province	2013, 2018, County level
GWW_{dom}	Domestic groundwater withdrawals		
GWW_{ind}	Industrial groundwater withdrawals		
GWW_{env}	Environmental groundwater withdrawals		
WDP_{ind}	Proportion of industrial water demands supplied by local surface water	Statistical Yearbook of cities in Hebei (Da and Wang, 2018; Fan and Wei, 2018; Huo, 2019; Lv, 2019; Wang, 2019; Yin, 2019; Zhao and Wang, 2019)	Annual, Municipal level
WDP_{dom}	Proportion of local surface water allocated to the domestic sector	Urban Construction Statistical Yearbook of cities in Hebei (Zhao, 2016)	2000–2018, Municipal level
RS_{local}	The China natural runoff dataset (CNRD v1.0)	https://data.tpdc.ac.cn/en/data/8b6a12c7-c8f9–465a-b449–852fbff51853/ (Miao et al., 2022)	1961–2018, monthly, 0.25°
R_{flood}	Proportion of flood discharge in flood season to surface water resources	Survey and Evaluation of China's Water Resources and Their Development and Utilization (General Institute of Water Conservancy and Hydropower Planning and Design, Ministry of Water Resources, 2014)	Multi-year averaged First-order watershed scale
A_{irr}	Effective irrigation area	Hebei Rural Statistical Yearbook (Zhao et al., 2019)	2000–2018, County level
GDP	Gross domestic product (GDP)	(Chen and Gao, 2021)	2000–2018, 1 km
N_{pop}	Population counts	WorldPop:: Population Counts (WorldPop, 2020)	2000–2018, 1 km
/	Upstream-downstream hydrographic connection	MERIT Hydro: global hydrography datasets (Yamazaki et al., 2019)	2019, 0.000833°
/	Land use:	Finer Resolution Observation and Monitoring - Global Land Cover (Yu et al., 2022)	1990–2020 every 5 years, 30 m

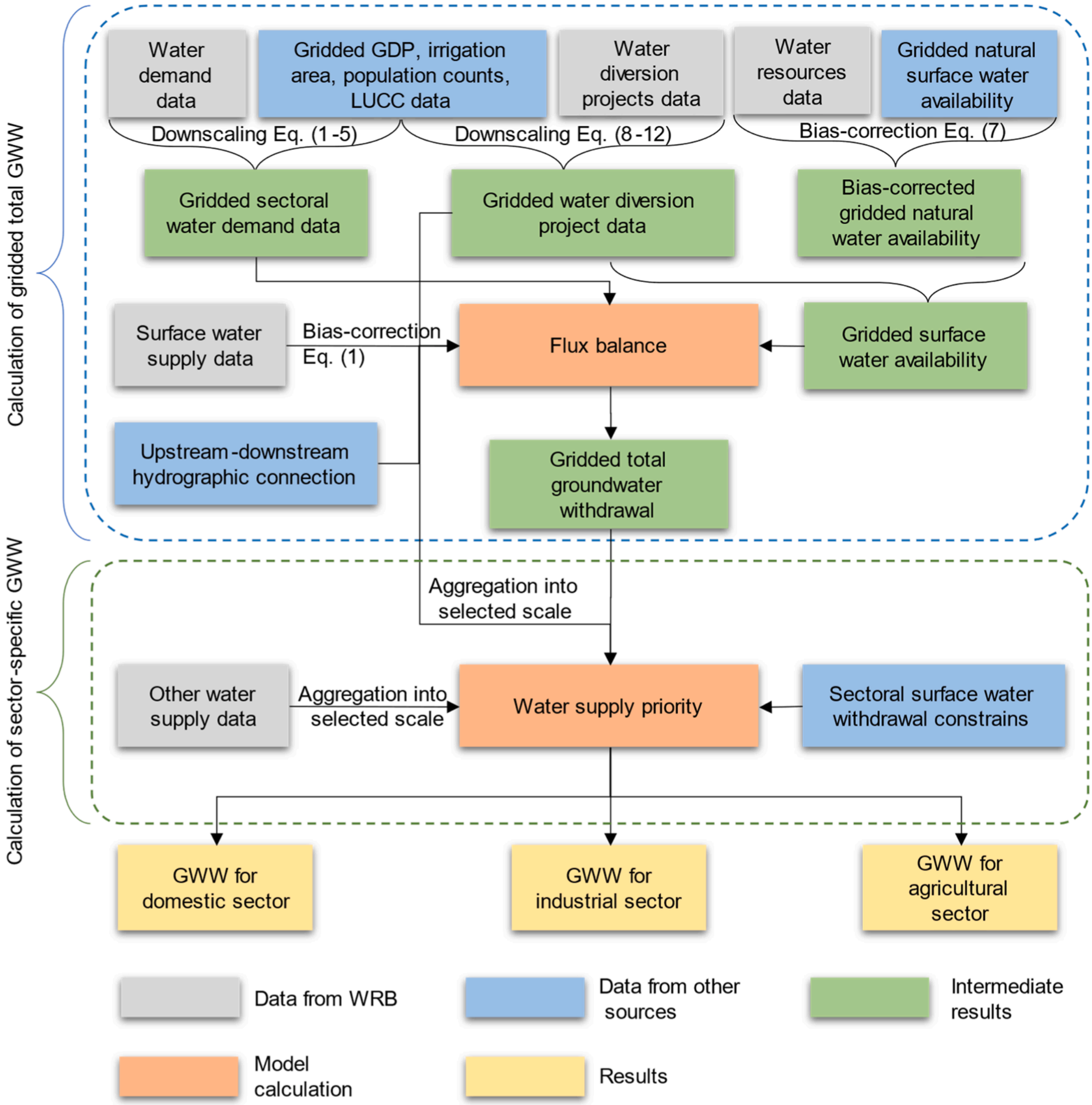

Fig. 2. Workflow for developing sector-specific groundwater withdrawals dataset.

identified by land use cover data.

$$Q_{agr}(i,j) = Q_{tot,agr} \times \frac{A_{irr}(i,j)}{\sum_{i,j} A_{irr}(i,j)} \tag{1}$$

$$Q_{ind}(i,j) = Q_{tot,ind} \times \frac{G(i,j)}{\sum_{i,j} G(i,j)} \tag{2}$$

$$Q_{dom}(i,j) = Q_{tot,dom} \times \frac{N_{pop}(i,j)}{\sum_{i,j} N_{pop}(i,j)} \tag{3}$$

$$Q_{env,urban}(i,j) = Q_{tot,env,urban} \times \frac{A_{imperm}(i,j)}{\sum_{i,j} A_{imperm}(i,j)} \tag{4}$$

$$Q_{env,eco}(i,j) = Q_{tot,env,eco} \times \frac{A_{water}(i,j)}{\sum_{i,j} A_{water}(i,j)} \tag{5}$$

where $Q_{agr}(i,j)$, $Q_{ind}(i,j)$, $Q_{dom}(i,j)$, $Q_{env,urban}(i,j)$, $Q_{env,eco}(i,j)$ [L^3] represent agricultural water demands, industrial, domestic water demands, urban public water demands and ecological water demands of grid (i, j), respectively. $Q_{tot,agr} Q_{tot,ind}$, $Q_{tot,dom}$, $Q_{tot,env,city}$, $Q_{tot,env,water}$ [L^3] represent agricultural, industrial, domestic, urban public and ecological water demands at provincial or municipal scale obtained from WRB. $A_{irr}(i,j)$ is the effective irrigation area of grid (i, j). $G(i,j)$ is GDP of grid (i, j). $N_{pop}(i,j)$ is population density of grid (i, j). $A_{imperm}(i,j)$, $A_{water}(i,j)$ are area of impervious layer and water body of grid (i, j).

The total water demands could be supplied with surface water, groundwater and other water sources (i.e., sewage recycling, seawater desalination, etc.). We excluded the other water sources from the total water demands (Eq. 6) in order to calculate the water demands supplied only by surface water and groundwater sources. Thus, we can distinguish the contribution of surface water and groundwater to meet the water demands (Section 3.3).

$$Q_{wd} = Q_{agr} + Q_{ind} + Q_{dom} + Q_{env} - Q_{ow} \tag{6}$$

where Q_{wd} [L^3/T] represents the sum of water supplied by surface water and groundwater sources. Q_{ow} [L^3/T] is other water sources.

3.2. Surface water availability

Based on WRB, water supply could be classified into three primary classes, i.e., surface water supply, groundwater supply, and other water supply. Surface water supply includes the resources from inter-basin water diversion projects like the South-to-North Water Diversion Project (SNWD) and Yellow River Diversion Project (YRD) in China. Based on WRB, natural surface water availability refers to the annually renewable dynamic water volume of the surface water bodies such as rivers, lakes, and glaciers, i.e., the runoff of local natural rivers (MWRC, 2014). In our study, we downscaled the local natural surface water availability into grid-level for further analysis.

3.2.1. Natural surface water availability

To study the natural surface water availability, we chose the China Natural Runoff Dataset (CNRD version 1.0), which provides monthly spatiotemporally continuous records of natural surface water availability (i.e., surface runoff) at a spatial resolution of 0.25° × 0.25° grid scale during 1961–2018 which have been validated against measurements from 200 hydrological gauge stations across China. The dataset was generated using the Variable Infiltration Capacity macroscale hydrological model, while the discrepancies in model structures, assumptions and parameters led to uncertainties in natural surface water availability simulations (Miao et al., 2022). Finally, annual provincial and municipal-level statistical WRB records of natural surface water availability was taken from the CNRD dataset during the period from 1961 to 2018, with bias corrected and deviation minimized using a correction factor (Eq. 7).

$$RS_{local,corr}(i,j,t) = RS_{local}(i,j,t) \times \frac{\overline{RS_{local,obs}(t)}}{\overline{RS_{local}(t)}} \tag{7}$$

Where $RS_{local,corr}(i,j,t)$ is the corrected natural surface runoff for the year t on grid (i, j), i.e. the amount of local surface water resources. $RS_{local}(i,j,t)$ is the natural runoff from the CNRD dataset for the year t on grid (i, j). $\overline{RS_{local,obs}(t)}$ is the surface water resources of the province or city where grid (i, j) is located for the year t in WRB. $\overline{RS_{local}(t)}$ is the sum of the gridded natural runoff of all grids in the city for the year t. This bias-corrected approach assures natural surface availability to be consistent with provincial or municipal-level statistics, which leads to more reliable GWW estimation.

3.2.2. Diverted water

Diverted water in this study means the water diverted through inter-basin water diversion projects from water bodies outside the study region. In Hebei Province, the diverted water comes from the SNWD and YRD projects. While the distribution of the diverted water utilization within water demands sectors has been well studied, the precise region of use remains ambiguous in most cases. In our study, the diverted water is assumed to be evenly distributed within the designated clear targeted region (Eq. 8). For example, the Yellow River Diversion Project in Hebei Province in China established a distinct water diversion route to rejuvenate the severely degraded Baiyangdian wetland. In comparison, we downscaled the sectoral diverted water within the unclear target area using the same scheme along with subsector water demands (Section 3.1). Specifically, diverted water designated for the agricultural, industrial, and domestic sector was downscaled based on effective irrigation area, GDP level and population density (Eqs.9–11). Environmental diverted water was allocated within river systems, lakes, and wetlands, with ecological diverted water uniformly distributed across each grid within water bodies (Eq. 12).

$$Q_{dw,t}(i,j) = Q_{tot,dw,t} \times \frac{A_t(i,j)}{\sum_{i,j} A_t(i,j)} \tag{8}$$

$$Q_{dw,agr}(i,j) = Q_{tot,dw,agr} \times \frac{A_{irr}(i,j)}{\sum_{i,j} A_{irr}(i,j)} \tag{9}$$

$$Q_{dw,ind}(i,j) = Q_{tot,dw,ind} \times \frac{G(i,j)}{\sum_{i,j} G(i,j)} \tag{10}$$

$$Q_{dw,dom}(i,j) = Q_{tot,dw,dom} \times \frac{N_{pop}(i,j)}{\sum_{i,j} N_{pop}(i,j)} \tag{11}$$

$$Q_{dw,env}(i,j) = Q_{tot,dw,env} \times \frac{A_{water}(i,j)}{\sum_{i,j} A_{water}(i,j)} \tag{12}$$

$Q_{dw,agr}(i,j), Q_{dw,ind}(i,j), Q_{dw,dom}(i,j), Q_{dw,env}(i,j)$ [L^3] are the diverted water for the agricultural, industrial, domestic, environmental sector of the grid (i, j), respectively. $Q_{dw,t}(i,j)$ [L^3] is diverted water with clear target area. $Q_{tot,dw,agr}, Q_{tot,dw,ind}, Q_{tot,dw,dom}, Q_{tot,dw,env}$ [L^3] are the amount of diverted water for the agricultural, industrial, domestic and environmental sectors at the provincial/municipal level in WRB. $A_t(i,j)$ is the area of the grid (i, j) that belongs to the target region.

3.3. Total groundwater withdrawals

We further calculated gridded total GWW combing gridded water demands and surface water availability based on the assumption that the surface water is withdrawn first, followed by the groundwater resources when surface water is insufficient, which is consisted with previous studies (Hanasaki et al., 2018; Wada et al., 2014).

First, the surface water availability on the grid was calculated as the sum of the bias-corrected local natural surface water availability, the incoming discharge from upstream grids, the return flow from non-agricultural sectors RF_{nonagr}, and the inter-basin diverted water Q_{dw} (Eq. 13). The return flow is the disparity between the total water demanded and the consumed water, denoting the portion of water that is destined to re-enter the surface or subsurface environment. In agricultural sector, the predominant pathway for return flow is the infiltration into the underground, thereby replenishing groundwater aquifers (Cao et al., 2013; Wada et al., 2012). Conversely, in domestic and industrial sectors, return flows traverse the urban tap water network and associated infrastructures, ultimately reintegrating with surface water bodies and subsequently contributing to downstream utilization (Flörke et al., 2013). Thus, the surface water availability on the grid is calculated as follows,

$$Q_{sw} = RS_{local,corr} + \sum_{j=1}^{n} \left(Q_{out,j} + RF_{domind,j}\right) + Q_{dw} \tag{13}$$

where Q_{sw} [L^3/T] is the total surface water availability of grid (i, j), $Q_{out,j}$ [L^3/T] is the outflow entering this grid from upstream grid j. RF_{domind} [L^3/T] is the return flow of domestic and industrial sectors from upstream grid j entering this grid. n is the number of upstream grids. Q_{dw} [L^3/T] is diverted water. Surface flow directions used to route water availability from upstream to downstream grid cells was obtained from MERIT hydro: global hydrography datasets (Yamazaki et al., 2019). This dataset was developed based on the MERIT DEM and multiple inland water maps containing the upstream-downstream hydrographic connection of surface water at the 3 arc-second spatial resolution (~90 m at the equator).

Second, total surface water available for human use ($Q_{sa}[L^3/T]$) was further calculated by subtracting flood water (Q_f [L^3/T]) and environmental flow requirement (EFR) from total surface water availability (Eq. 14). This is because flood water is unavailable for human use and part of surface water resources should be retained to maintain an ideal ecological environment for surface water bodies (Huang et al., 2023; Sun et al., 2020).

$$Q_{sa} = Q_{sw} - EFR - Q_f \tag{14}$$

$$Q_f = RS_{local,corr} \bullet R_{flood} \tag{15}$$

$$\begin{cases} EFR_m = 0.6 \times RS_{local,m}, & RS_{local,m} \le 0.4 \times RS_{local,a} \\ EFR_m = 0.3 \times RS_{local,m}, & RS_{local,m} > 0.8 \times RS_{local,a} \\ EFR_m = 0.45 \times RS_{local,m}, & 0.4 \times RS_{local,a} < RS_{local,m} \le 0.8 \times RS_{local,a} \end{cases} \tag{16}$$

where R_{flood} is proportion of flood discharge in flood season to surface water resources. Monthly EFR was calculated using the variable monthly flow (VMF) method developed by Pastor et al. (Veldkamp et al., 2017) (Eq. 16). $RS_{local,m}$ and $RS_{local,a}$ [L^3/T] represent the natural runoff of month m and the natural runoff of the year respectively. The VMF method first identifies low, medium, and high flow months and then assesses monthly environmental flow requirement by increasing protection of freshwater ecosystems during low flow seasons.

Based on the assumption, human water demands for a specific grid was first met by surface water withdrawals (Q_{su} [L^3/T]), and the remaining water would flow to downstream areas. Total surface water withdrawals on a grid can be estimated as:

$$Q_{su} = \min(Q_{wd}, \quad Q_{Sa}) \tag{17}$$

To ensure that the total value of the calculated gridded surface water withdrawals at the municipal or provincial level equals to the statistical data in the WRB, we performed bias correction on the calculated gridded surface water withdrawals (Eq. 18).

$$R_{sw} = \frac{\overline{Q_{su,report}}}{\overline{Q_{su,cal}}} \tag{18}$$

$$Q_{su,corr} = R_{sw} \bullet Q_{su} \tag{19}$$

where R_{sw} is the correction factor. $\overline{Q_{su,report}}$ [L^3/T] is statistical data of surface water withdrawals of the city or province where the grid is located in the WRB. $\overline{Q_{su,cal}}$ [L^3/T] is the sum of the gridded surface water withdrawals within the city or province where the grid is located. $Q_{su,corr}$ [L^3/T] is corrected surface water withdrawals.

When the surface water supply cannot fully meet the human water demands, only *EFR* will flow into the downstream area. If Q_s is greater than $WU_{s,corr}$, the remaining surface water will flow into the downstream area (Eq. 20).

$$Q_{out} = \min\left(EFR, \quad Q_{sw} - Q_{su,corr}\right) \tag{20}$$

where Q_{out} [L^3/T] is the outflow that is available to surface water uses of downstream grids. GWW (Q_{gu} [L^3/T]) occurs only when surface water availability is insufficient to meet human water demands (Eq. 21).

$$Q_{gu} = \max\left(0, \quad Q_{wd} - Q_{su,corr}\right) \tag{21}$$

3.4. Sectoral groundwater withdrawals

Gridded surface water and GWW, subsector water demands, the inter-basin diverted water were upscaled to designated regional level such as basin, city or county levels through a multi-step process.

3.4.1. Sectoral surface water withdrawals constraints

The range of the calculated sectoral surface water withdrawal was limited by the values from current available datasets (e.g. WRB or city Statistical Yearbook). First, local surface water withdrawals $Q_{sw,local}$ was calculated as total surface water withdrawals Q_{sw} minus diverted water (Eq. 22). Second, the data from the city Statistical Yearbook provides industrial surface water use $WU_{ind,sw}$ and total wateruse $WU_{ind,tot}$, and the proportion of industrial water demands supplied by surface water $WUP_{ind,sw}$ was calculated by Eq. 23. The industrial surface water use $Q_{ind,sw}$ was then calculated (Eq. 24). In addition, the groundwater and total water supply capacity of municipal urban water plants $WU_{dom,gw}$, $WU_{dom,tot}$ were obtained from the city's Statistical Yearbook of Urban Construction, and the proportion of non-groundwater sources of municipal domestic sector $WUP_{dom,nongw}$ was calculated using Eq. 25.The proportion of surface water supply to domestic sector $WDP_{dom,sw}$ was obtained by domestic water demands in the WRB multiplied by $WUP_{dom,nongw}$ and then divided by local surface water supply (Eq. 26). The domestic surface water use $Q_{dom,sw}$ is the minimum value between the total domestic water demands and the proportion of surface water supply to domestic sector multiplied by the local surface water supply (Eq. 27). In order to reduce the impacts of the inter-basin water diversion projects on the local surface water supply ratio, we assume that the ratio remained the same prior to the implementation of those projects until the end of the simulation. Missing years were treated with data from the years nearby, and missing cities were substituted with the average values from adjacent cities. Moreover, the environmental sector's water utilization, including both urban public water and ecological water for water body replenishment, predominantly relies on surface water and other water sources. For environmental sector, zero GWW was used.

$$Q_{sw,local} = Q_{sw} - Q_{dw} \tag{22}$$

$$WDP_{ind,sw} = \frac{WU_{ind,sw}}{WU_{ind,tot}} \tag{23}$$

$$Q_{ind,sw} = WD_{ind} * WDP_{ind,sw} \tag{24}$$

$$WUP_{dom,nongw} = 1 - \frac{WU_{dom,gw}}{WU_{dom,tot}} \tag{25}$$

$$WDP_{dom,sw} = \frac{WUP_{dom,nongw} \times WD_{dom}}{Q_{sw,local}} \tag{26}$$

$$Q_{dom,sw} = \min(WD_{dom}, WDP_{dom,sw} \times Q_{sw,local}) \tag{27}$$

3.4.2. Priority of water supply

Fig. 3 displays the water-supply priority for GWW in each sector in three steps. First, the priority of water supply is determined based on the characteristics and purposes of various water sources. Surface water is available for use in all sectors, while groundwater is accessible to all sectors except the environmental sector. Surface water takes precedence over groundwater in utilization due to its convenience and lower cost compared to groundwater. Other water sources, primarily generated with high costs, such as sewage recycling and seawater desalination, are unlikely to be considered by the agricultural sector. It is important to note that, diverted water is mainly used for domestic, industrial, and environmental sectors, among which SNWD diverted water is mainly used to replace groundwater in domestic and industrial sectors with domestic sector as priority (Long et al., 2020). Second, the sequencing of calculations for each sector is determined by the order of water resources allocated among the environmental, domestic, industrial, and agricultural sectors. Since we assumed that the environmental sector does not utilize groundwater, the calculation of environmental water usage was prioritized to facilitate the determination of surface water resources available for the remaining three sectors. After that, domestic water usage was calculated, followed by industrial water demands and agricultural water demands. Third, we identified the order of different water sources utilization within each sector, i.e., (1) The environmental sector prioritized the use of diverted water for ecological use, followed by the other water sources, and local surface water. (2) The domestic sector gives priority to the use of local surface water (with restrictions), diverted water for domestic use, other source water, and groundwater. (3) The industrial sector gives priority to the use of local surface water (with restrictions), diverted water for industrial use, other source water, and groundwater. (4) The agricultural sector prioritizes the use of diverted water for agricultural use, residual surface water (including remaining diverted water), and groundwater. The water consumption from different sectors and water sources in selected scale were calculated following this scheme, as shown below.

3.5. Model validation

To evaluate the performance of the methodology, we calculated correlation coefficient R and the normalized root mean squared error (NRMSE) between the simulated results and available statistical data stratified by year and sector, respectively. R and NRMSE are defined as follows,

$$R = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{22}$$

$$NRMSE = \frac{\sqrt{\sum_{i=1}^{n}(\widehat{y}_i - y_i)^2}}{\max(y_i) - \min(y_i)} \tag{23}$$

n is the total number of samples. $\widehat{y}_i$, y_i are predicted values and observed values respectively. The NRMSE ranges from 0 (perfect fit) to 1. The denominator ensures that the metric is normalized by the variability in the observed data, providing a meaningful measure of relative predictive accuracy. The correlation coefficient R varies from −1 (perfect negative correlation) to 1 (perfect positive correlation), 0 means no linear correlation.

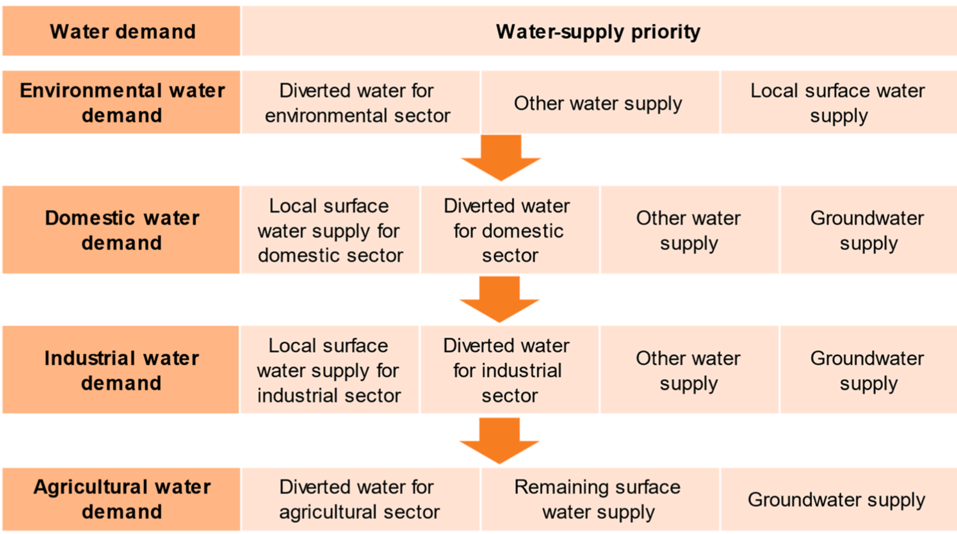

Fig. 3. Water-supply priority for GWW of each sector.

3.6. Piecewise linear regression analysis

We adopted the piecewise linear regression to identify the turning points in GWW trend and fit multiple linear models for each sector. A continuous piecewise linear regression model with multiple turning points for a GWW time series is expressed as follows (Zhou et al., 2020),

$$GWW = \begin{cases} \alpha_0 + \alpha_1 t + \varepsilon, \quad t \le Y_1 \\ \alpha_0 + \alpha_1 t + \sum_{i=1}^{I-1} \alpha_{i+1}(t - Y_i) + \varepsilon, \quad t\epsilon(Y_i, Y_{i+1}) \\ \alpha_0 + \alpha_1 t + \sum_{i=1}^{I} \alpha_{i+1}(t - Y_i) + \varepsilon, \quad t > Y_I \end{cases} \tag{25}$$

where t is year, α_0, α_1, and α_{i+1} are regression coefficients, and ε denotes the residual of the regression. The GWW slope is α_1 before the year Y_1, $\sum_{i=1}^{I}\alpha_i$ during the period from Y_i to Y_{i+1}, and $\sum_{i=1}^{I+1}\alpha_i$ after the Y_I. The least-squares error technique is applied to fit the model observations, determining Y_i and α_i (i = 0 to I + 1). The necessity of introducing turning points is tested statistically with the t test under the null hypothesis that αi (i = 2 to I + 1) are not different from zero (Zhou et al., 2020). The diagnostic statistics for the regression also include the goodness-of-fit (R_2), the P value for the entire model, and the P values for the trends of each section. $P <$ 0.01 is considered as significant.

4. Results and discussion

4.1. Validation

We first validated the obtained GWW against WRB data at the provincial and municipal scale and the results illustrated satisfactory consistence. The gridded total GWW estimates were aggregated at provincial and municipal scales and compared with WRB data. The validation datasets from WRB were released by the Department of Water Resources of Hebei Province, which is authoritative and reliable. At the provincial scale, both datasets show consistent trend and values, with NRMSE of 0.08 and correlation coefficient of 0.99 from 2000 to 2018 (Fig. 4(a)). Since the municipal-scale GWW from WRB began to be recorded in 2010, we only verified the municipal data of 2010–2018. At the municipal scale, the calculated GWW closely aligned with the WRB values (Fig. 4(b)), the correlation coefficient between calculated results and statistical data is 0.97 and the normalized root mean squared error is 0.08. Together these results highlight the reliability and accuracy of our methodology in estimating GWW.

Second, we verified the calculated county-level sector-specific GWW against the county-level sectoral GWW of the dataset from the Department of Water Resources of Hebei Province for 2013 and 2018 (Fig. 5) and found that our methodology well predicted the annual sectoral GWW. The predictions are aligned with the statistical data for most data points located near the 1:1 line (Fig. 5). The correlation coefficients between the simulated and the observed values of total GWW from 2013 and 2018 are above 0.4 while the NRMSE values are below 0.25. The R-values of the agricultural sector fluctuates are around 0.4, and the NRMSE values are below 0.3. The R-values of the industrial sector are 0.75 and 0.68 in 2013 and 2018, respectively, while the NRMSE values are lower than 0.2. The R-values of the domestic sector are higher than 0.5, and the NRMSE values are below 0.2. Together those results suggest our methodology is effective and robust.

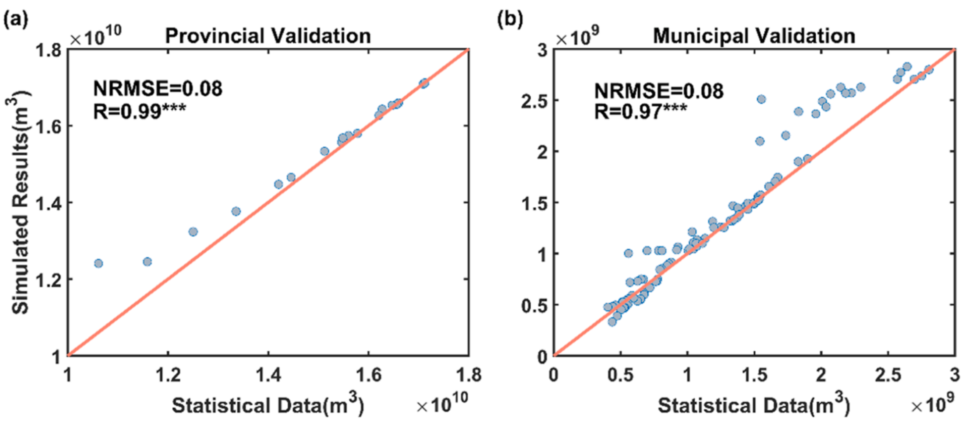

Fig. 4. Validation of the simulated gridded GWW. (a) Comparethegridded GWW aggregated to provincial scalewith the statistical data from 2000 to 2018; (b) Compare the gridded GWW aggregated to municipal scale against statistical data from 2010 to 2018. The statistical data are from Hebei Water Resources Bulletin. *** denotes the significance level $\alpha < 0.001$.

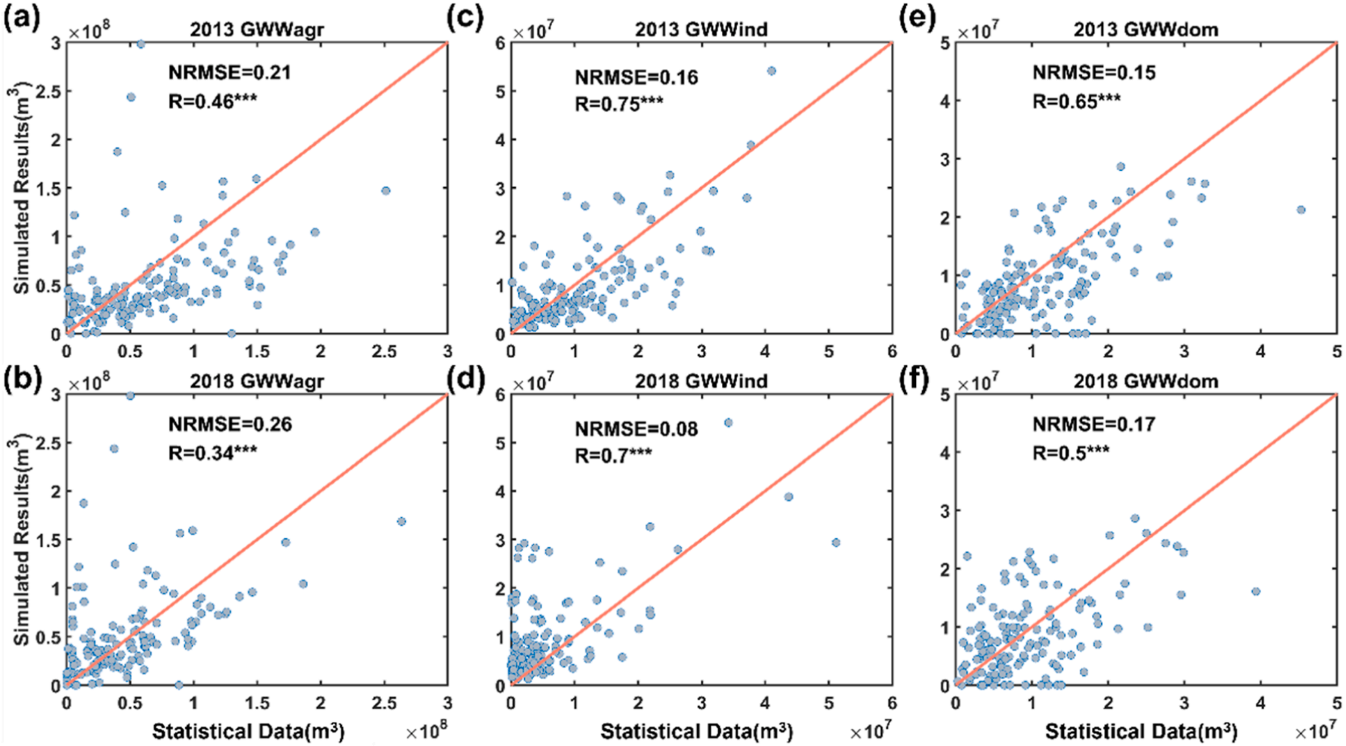

Fig. 5. Validation of the simulated county/district-scale total and sector-specific GWW. Comparison of the simulated (a-b) agricultural GWW, (c-d) industrial GWW and (e-f) domestic GWW on county/district scale with the statistical data in 2013 and 2018 provided by Department of Water Resources of Hebei Province. *** denotes the significance level $\alpha < 0.001$.

4.2. Spatial-temporal pattern of sectoral groundwater withdrawals

We first calculated multi-year averaged sectoral GWW and analyzed the spatial pattern of the results (Fig. 6). The spatial pattern of total GWW is determined based on the spatial pattern of agricultural sector since that the groundwater constitutes more than 80 % of the total agricultural water supply in Hebei Province (Tian et al., 2016). In contrast, domestic and industrial GWW account for ~10 % of the total GWW due to their preference over the surface water sources especially the diverted water resources. The highest total and agricultural GWW occurred in Gaocheng District in Shijiazhuang City, with an annual mean value of 0.29 billion m^3 and 0.25 billion m^3, indicating the scarce of surface water resources in this district thus a heavy dependence of agriculture on groundwater. Further analysis of the irrigated area data of Gaocheng District indicates that the most significant agricultural water demands in this region come from its irrigated area of about 550 square kilometers, accounting for more than half of the jurisdiction of Shijiazhuang City. The highest industrial GWW is from Qian'an District in Tangshan City (35 million m^3) due to the district has advanced industrial development with the highest GDP across all counties and districts in Hebei Province. In comparison, the domestic sector is shown less dependent on groundwater across all counties and districts in Hebei. The highest domestic GWW is from Yuhua District, a municipal district of Shijiazhuang City (32.2 million m^3), densely populated and with significant domestic water requirements.

To detect the temporal changes of the sectoral GWW, we conducted a piecewise linear regression (PLR) analysis on the simulation results and found turning points of each sector (Fig. 7) as well as possible driven factors. The total groundwater supply peaked in 2014, which is aligned with the implementation of water diversion projects and policies to compress groundwater extraction at that time. Hebei Province has also implemented a series of policies to manage groundwater over-exploitation since 2014. In rural regions, new strategies have been adopted, including water-saving agricultural practices like adjusting cropping patterns (e.g., seasonal fallowing, rain-fed farming, afforestation of reclaimed land, etc.) and promoting efficient irrigation methods (e.g., drip irrigation, sprinkler irrigation). National Water Conservation Action Plan has also been implemented in urban areas with the emphasis on industrial water reduction and rainwater utilization like the sponge cities. Efforts have been made to expedite the South-to-North Water Diversion

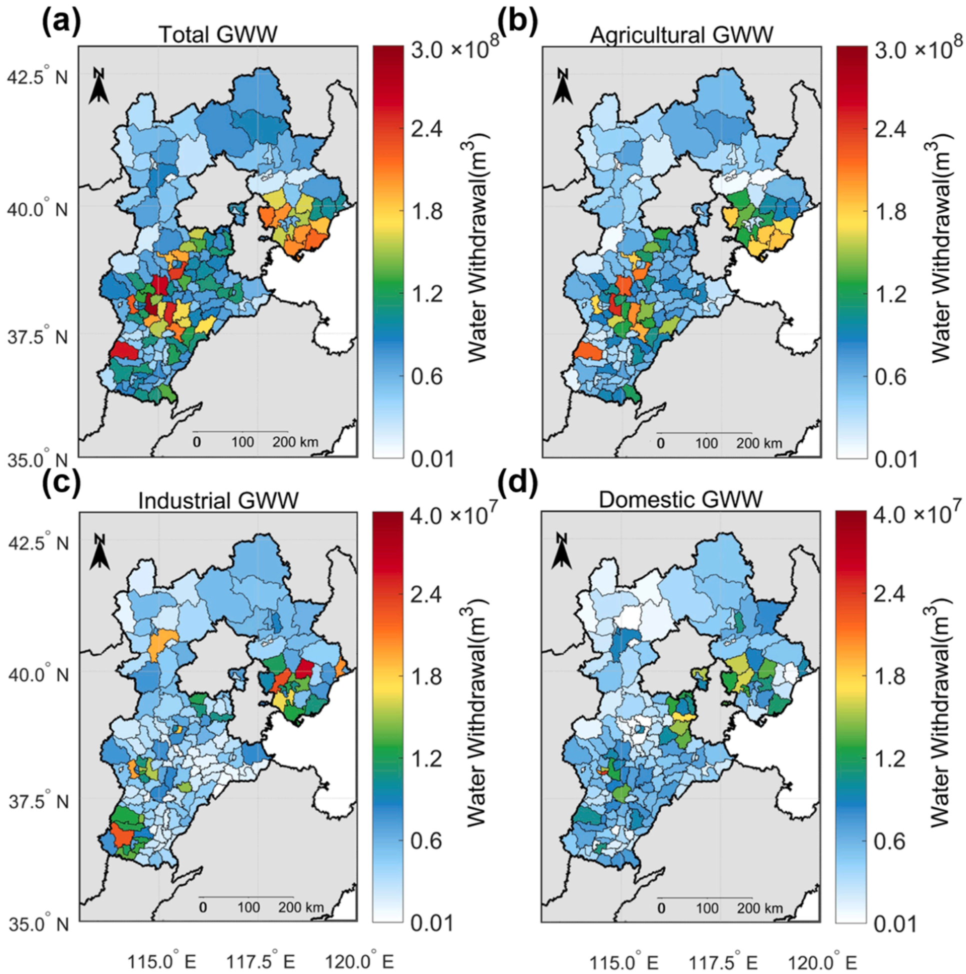

Fig. 6. Multi-year averaged (a) total GWW and of (b) agricultural sector, (c) domestic sector, and (d) industrial sector at county level in Hebei Province in 2000–2018.

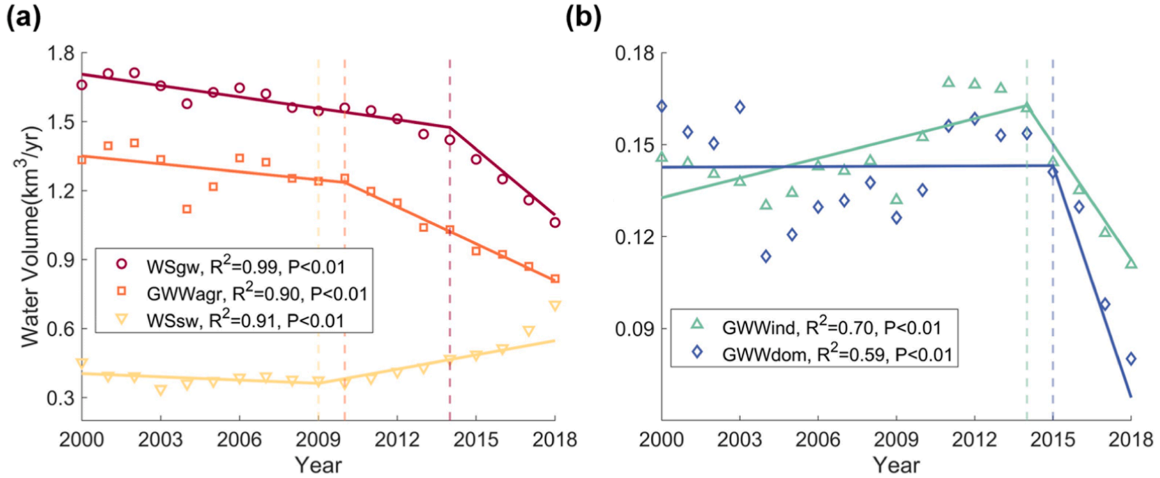

Fig. 7. Turning points for groundwater and surface water supply, agricultural, industrial and domestic GWW. The scatters represent statistical data and the solid lines denote the simulated results from PLR model. Dashed lines perpendicular to the x-axis refer to the year of the occurrence of the turning points. For the meaning of the colors, deep red and shallow yellow mean groundwater and surface water supply, respectively. Orange, shallow green and blue mean agricultural GWW, industrial GWW and domestic GWW. For the meaning of the shape of scatters, the circle represents the groundwater supply, the inverted triangle represents the surface water supply, and the square, equilateral triangle, and diamond represent the groundwater withdrawals in the agricultural, industrial and domestic sectors respectively.

Project to replace urban groundwater usage in water-receiving areas. Surface water utilization and industrial restructuring have also been prioritized in non-water-receiving areas to mitigate groundwater depletion (The People's Government of Hebei Province, 2018).

In addition to the total groundwater supply, we further examined the turning points of groundwater usage across various sectors. It is noticed that the agricultural sector's water usage changed in the year 2010, following the surface water supply increase in 2009. This indicates that the decreasing dependence on groundwater was possibly due to increased surface water supply since the surface water could be easily and conveniently accessed by farmers for agricultural irrigation. In comparison, the domestic and industrial sectors have less water demands, and the portion of local surface water usage are relatively fixed, which might explain its lower sensitivity to increased surface water supply in those sectors. In industrial sector, GWW trend changed around 2014, corresponding to the initiation of water diversion projects and the implementation of water-saving policies in the industrial sector. Similarly, GWW trend started to change 2015 in the domestic sector, possibly due to the increasing water demands in the domestic sector. The SNWD project was initiated in 2014 with limited diverted water; the volume of water diversion increased annually starting 2015, posing a substitution effect on groundwater sources for the domestic sector. Together our analysis revealed that the variations in groundwater extraction across different sectors in Hebei Province reflect the changes in the water supply structure, influenced by policy regulations and water diversion projects.

Based on the aforementioned PLR results, it is evident that the turning point for groundwater extraction occurred in 2014. Consequently, we divided the study period into two segments: P1 (2000–2014) and P2 (2014–2018). We calculated the differences at the beginning and end of each stage to analyze the variations across different counties and districts between these two periods (Fig. 8). There were 11 counties and districts with substantial increases in total groundwater extraction (exceeding 60 million m^3) during the P1 period but decreases during the P2 period, likely driven by the implementation of water diversion projects and policies. Xushui District in Baoding City, on the other hand, showed an increase in total groundwater extraction during the P2 period, mainly due to an increase in agricultural GWW in that region. Hengshui City had the most stringent implementation of groundwater management policies in Hebei Province. Agricultural GWW decreased in various counties of Hengshui City during the P2 period, suggesting an effective agricultural and water conservation policy implementation in those areas. The reduction in domestic and industrial GWW during the P2 period is primarily attributed to the water supply provided by the SNWD Project. During the P1 period, domestic groundwater extraction increased in most counties in central and northeastern coastal regions of Hebei Province; while the extraction was widely reduced over the entire province during the P2 period. Similarly, industrial groundwater extraction increased in most counties in the northeastern part of Hebei Province during P1 period while the extraction showed an evident decreasing trend in the same counties and regions during the P2 period.

In summary, our study has calculated sector-specific groundwater withdrawal data at the county-level for Hebei Province from 2000 to 2018. This data offers a higher spatial resolution compared to existing publicly available datasets, which aids the government in formulating policies tailored to local conditions. It also enables the calculation of annual variations in sector-specific groundwater withdrawals at the county level. This higher temporal resolution more accurately reflects the temporal changes in the dependency of various sectors on water resources due to human activities. Furthermore, the calculation process comprehensively considers the availability and actual utilization of both surface water and groundwater resources, which is rather consistent with the actual situation than the WaterGAP 2.2d model's assumption (Müller Schmied et al., 2021).

It is possible to calculate the sectoral GWW in other areas using the technical approach and the water supply priority framework

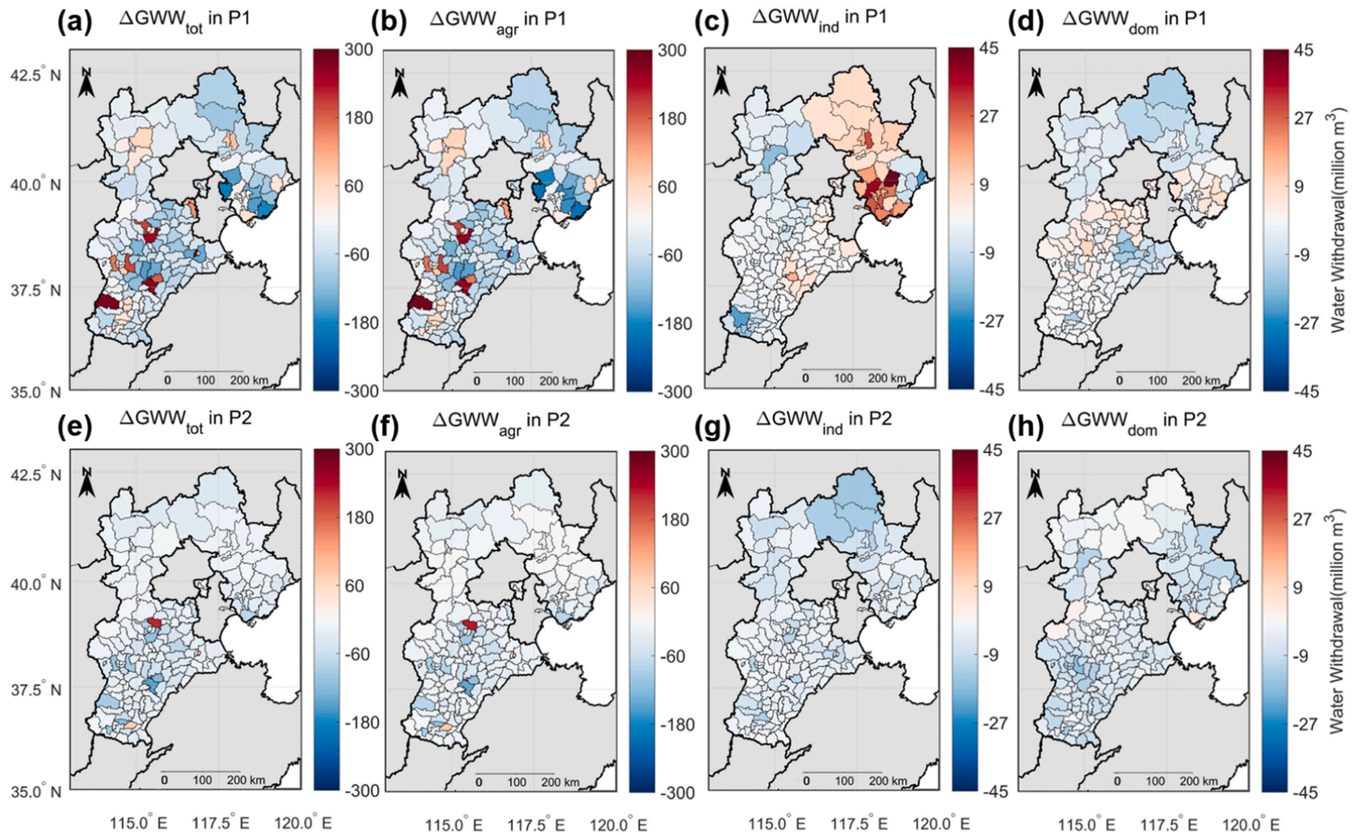

Fig. 8. The spatial pattern of the differences at the beginning and end of each stage of total GWW and GWW for agricultural, domestic, and industrial sector in P1 period ((a)-(d)) and P2 period ((e)-(f)), respectively.

proposed in this research by replacing the input data mentioned in this study with corresponding data from other regions. The water balance method is widely applicable, while the order of water source allocation may vary across different regions. To reduce simulation errors, adjustments to water supply priorities can be made based on local government policies. Validation data can be collected through official statistical reports from local governments (which may require a formal request as they could be non-public data) or by searching for regional statistical reports and literature.

5. Conclusions

A methodology based on flux balance and water supply priorities to quantify sector-specific groundwater withdrawals was developed and carried out in Hebei Province, China. Agricultural groundwater withdrawals accounts for about 80 % of total groundwater withdrawals and dominates the spatial pattern of the total groundwater withdrawals. Total groundwater withdrawals decreased faster after the turning point of 2014 aligning with the implementation of water diversion projects and policies to compress groundwater extraction. This study underscores a significant role of inter-basin water diversion projects and groundwater extraction compressing policies in alleviating groundwater over-extraction.

However, some limitations should be noted in our approach. First, there were uncertainties associated the downscaling of the administrative sectoral water demands since accurate depiction of the grid-scale water supply pattern is challenging. Further improvements in our methodology and datasets are necessary. In addition, our methodology is unable to predict future water supply scenarios due to constraints of spatio-temporal data, which may hinder comprehensive investigations into the evolution of water supply structures. To enhance the simulation prediction in water supply scenarios, future studies can focus on the optimization of this methodology by adjusting input data indicators. For instance, domestic water demands can be adjusted as daily domestic water consumption per capita multiplied by population. Industrial water demands can be calculated as the amount of gross value added (GVA) and its corresponding water consumption per GVA. Agricultural water demands can be represented by the crop planting area and irrigation quota. Furthermore, it'll be beneficial if the applicable research period could be extended so that future periods could be covered in our approach, not only for water usage related studies, but also for making water management policies.

Our methodology is the first to take into account the impact of water diversion projects on sector-specific GWW with assumptions like the diversion of water replaces groundwater usage, and the environmental sector does not use groundwater. These assumptions are applicable not only to the local characteristics of Hebei Province but also in a broader scope, suggesting that similar analysis could be performed all over the country. Our upscaling process enable us to flexibly adjust the studies into targeted scales. Most importantly, we further categorized the water sources based on the sector-specific water usage so that human groundwater consumption and the related impact assessment could be quantified. Overall, our study provides an efficient and reliable tool for global-scale research on water resource management.

CRediT authorship contribution statement

Jiadi Zou: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Hongwei Cai:** Writing – review & editing, Methodology, Data curation. **Yan Bo:** Writing – review & editing. **Chenxi Xia:** Writing – review & editing. **Jin Fu:** Writing – review & editing. **Yazhen Gong:** Writing – review & editing, Validation. **Jinxia Wang:** Writing – review & editing. **Feng Zhou:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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