Journal of Hydrology: Regional Studies 61 (2025) 102715

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Crop irrigation water requirements mismatch the actual water allocation in the anthropogenic-regulated Yellow River Basin

Yueman Hou[a], Shuai Wang[a,*,1], Shuang Song[a,b], Peng Chen[c], Xutong Wu[a]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[b] Department of Co-evolution of Land Use and Urbanisation, Max Planck Institute of Geoanthropology, Jena 07745, Germany
[c] Chongqing Jinfo Mountain Karst Ecosystem National Observation and Research Station, School of Geographical Sciences, Southwest University, Chongqing 400715, China

ARTICLE INFO

Keywords:
Irrigation water requirement
Spatiotemporal mismatch
Agricultural water management
Yellow River Basin

ABSTRACT

Study area: The Yellow River Basin (YRB) in China is a critical grain-producing region that experiences severe water scarcity and intense competition for water resources.
Study focus: Agricultural irrigation is the primary water use in the YRB. However, the spatiotemporal patterns and alignment between irrigation water requirement (IWR) and supply remain unclear. This study quantified the spatiotemporal variations in IWR in the YRB, focusing on the alignment within the irrigation system. A process-based crop water model was used to calculate IWR for five major crops from 2001 to 2100, with future projections under three Shared Socioeconomic Pathways. The spatiotemporal patterns of total IWR and whether they align with actual irrigation water use and supply were analyzed.
New hydrological insights for the region: IWR in the highest irrigation areas exceeded 500 mm/yr. Two annual peaks were identified: March to May and July to August. Spatial and seasonal mismatches in the irrigation system were evident. Spatially, irrigation water use exceeded requirements in the source regions and upper reaches but failed to meet requirements in the middle and lower reaches. Seasonally, irrigation water supply peaked earlier than crop water requirements. Future projections suggest that seasonal mismatches will persist and may intensify due to delayed requirement peaks and increasing requirements. These findings highlight the importance of institutional adaptation in enhancing water resilience and sustainability in the Anthropocene.

1. Introduction

Freshwater use is exceeding the planetary boundaries, while global and regional water crises and scarcity risks continue to rise (Rosa et al., 2020; Mekonnen and Hoekstra, 2016). Agriculture remains the largest consumer of freshwater, with irrigation agriculture accounting for 72 % of global surface and groundwater withdrawals (Wisser et al., 2008; J. Zhang et al., 2021). Water is a key limiting factor for crop growth and development, directly affecting crop yield and quality (Mueller et al., 2012). Efficiently utilising limited water resources to meet agricultural irrigation requirements has become an urgent global challenge. Irrigation plays a crucial role in

* Corresponding author.
E-mail address: shuaiwang@bnu.edu.cn (S. Wang).
[1] Present address: No. 19 Xinjiekouwai Street, Haidian District, Beijing 100875, China.

https://doi.org/10.1016/j.ejrh.2025.102715
Received 25 July 2025; Accepted 13 August 2025
Available online 21 August 2025

enhancing the productivity of existing croplands (Elliott et al., 2014), contributing approximately 40 % of the global food production from irrigated crops (Mrad et al., 2020). Accurately estimating agricultural irrigation water requirements is essential for ensuring food production with efficient allocation of irrigation water resources.

Over half (52 %) of global irrigation expansion has occurred in water-stressed regions by the 21st century (Mehta et al., 2024). Agricultural water requirements have further strained regional water supplies (McDermid, 2024). Therefore, focusing on the spatiotemporal matching of irrigation water supply and requirements is necessary. For instance, from a spatial perspective, the expansion of irrigated cropland in northern China has exacerbated the spatial mismatch between water and arable land, increasing the risk of water scarcity (Qi et al., 2022). The spatial mismatch between agricultural regions and available water in the western United States has led to increasingly severe groundwater overexploitation (Scanlon et al., 2012). Weak irrigation infrastructure in Africa limits the adequate water supply, constraining agricultural development (Giordano et al., 2023). Some irrigated areas globally will shift from irrigation to rainfed agriculture due to freshwater limitations by the end of this century, leading to a loss in crop yields (Elliott et al., 2014). From a temporal perspective, the earlier meltwater availability in South Asia does not align temporally with the increasing irrigation requirement, leading to a greater reliance on non-renewable groundwater during critical agricultural periods (Lutz et al., 2022). In typical arid basins of Central Asia, the peak agricultural irrigation period does not align with the peaks of natural precipitation and surface water availability (Peng et al., 2023). The above highlights a widespread mismatch between agricultural irrigation requirements and the spatiotemporal distribution of water resources. Therefore, anthropogenic water resource management and coordination are essential for alleviating supply-requirement conflicts and improving agricultural water use efficiency.

The Yellow River Basin (YRB) is a typical anthropogenic-regulated river system where extensive construction of check dams, reservoirs, and irrigation projects has significantly altered the spatiotemporal distribution of water resources (Fu et al., 2017; Wu et al., 2025). Therefore, the basin provides an ideal case for studying the matching between irrigation water supply and requirement. As an important agricultural production area in China, the YRB faces conflicts between water supply and requirement (Chen et al., 2020; Li et al., 2021). To mitigate these conflicts, the Yellow River Conservancy Commission of the Ministry of Water Resources (YRCC) has implemented unified water scheduling since 1999 (Wang et al., 2019), successfully reducing water usage (Song et al., 2024). However, it remains unclear whether these allocation schemes truly matches the water requirement of agricultural irrigation systems. Existing research on the water supply and requirement relationship in the YRB primarily focuses on a macro level, often treating the water resource system as a whole. For example, Liu et al.(2022) quantified the total water supply and requirement, revealing a pronounced

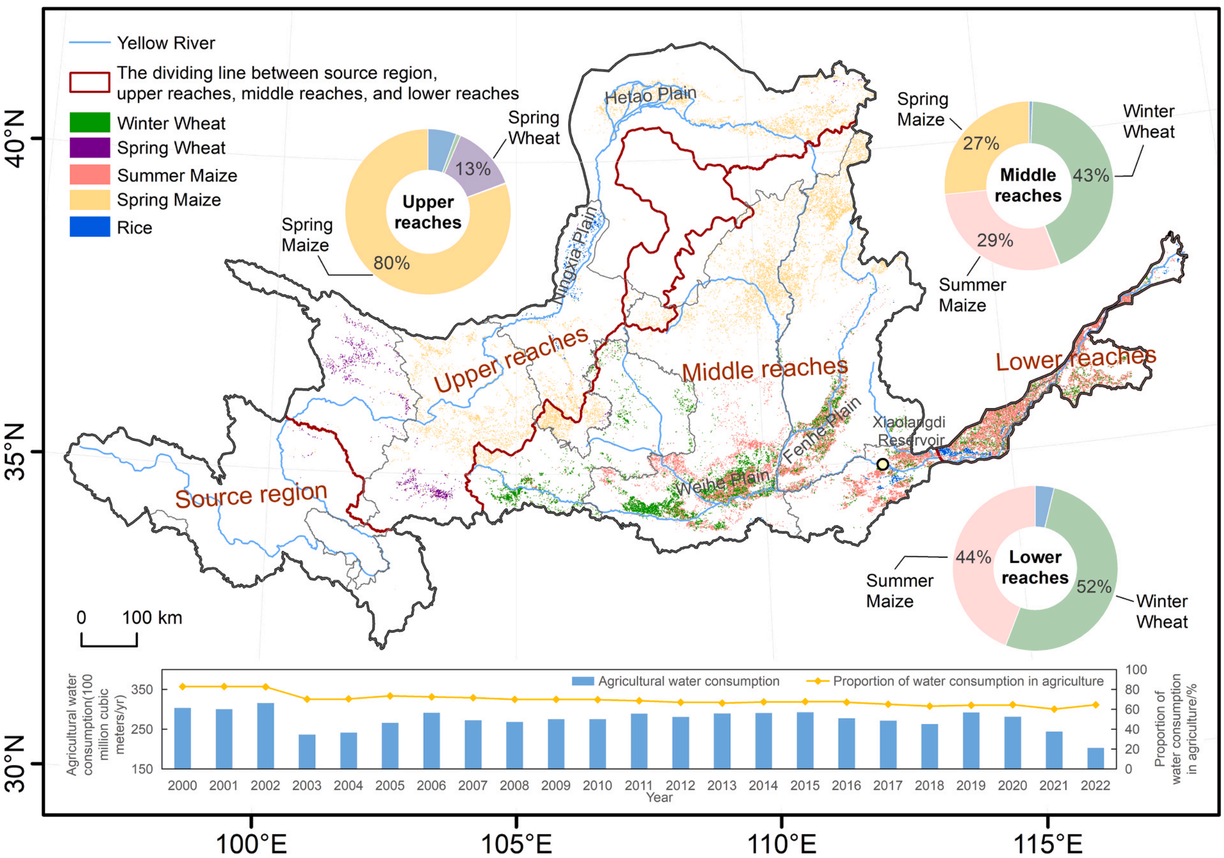

Fig. 1. Spatial Distribution of Major Grain Crops and Agricultural Water Consumption in the YRB. (Geographic location information, such as the Ningxia Plain, is referenced from http://bzdt.ch.mnr.gov.cn/).

spatial mismatch between them. Zhang et al. (2023) predicted the total water supply and requirement, highlighting the imbalance in the planned years. However, these studies fail to capture the internal supply-requirement dynamics within the agricultural irrigation system and overlook the unique water supply indicators of the Yellow River, limiting the precision and adaptability of water resource management in the basin. Regarding food-water systems, existing research has mainly concentrated on the requirement side, using crop water requirement models to calculate crops' water requirements or footprint (Liu et al., 2022; Zhuo et al., 2016; Wang and Shi, 2024; Chiarelli et al., 2020). However, less attention has been given to matching irrigation supply and requirements, making it difficult to assess the efficiency and rationality of water allocation.

To address the above research gaps, this study focuses on the spatiotemporal matching of the irrigation system in the YRB. Using a process-based crop water model, we developed a high-resolution dataset of irrigation water requirements for major grain crops in the YRB from 2001 to 2100. We analyzed their spatiotemporal patterns, tested whether the total irrigation water requirements align with actual water use and supply, and projected future changes through to 2100.

2. Materials and methods

2.1. Study area

The YRB stretches across northern and central-western China. From southeast to northwest, it spans semi-humid (54.8 % of the basin area), humid (5.3 %), semi-arid (28.2 %), and arid (11.7 %) regions (Ma et al., 2012). The basin's annual average precipitation ranges from 200 mm to 1000 mm, with most areas receiving between 200 mm and 650 mm (Jian et al., 2023). It is a crucial grain production area in China, with major crops including winter wheat, spring wheat, summer maize, spring maize, and rice (Fig. 1; Luo et al. 2020, based on 2010 crop distribution). The phenology of crops are shown in Table S1 of Supplementary material 1. Regarding planting proportions for the five crops (Luo et al.2020, based on the average values from 2000 to 2019), the upper reaches are predominantly planted with spring maize, accounting for 80 %. In the middle reaches, winter wheat has the highest proportion (43 %), followed by summer maize (29 %) and spring maize (27 %). In the lower reaches, a crop rotation system is implemented between winter wheat and summer maize, with nearly equal planting proportions of 52 % and 44 %, respectively. From the perspective of water usage structure (Fig. 1; based on data from the Yellow River Water Resources Bulletin (http://www.yrcc.gov.cn/gzfw/szygb/), the detailed data are provided in Supplementary material 2), agricultural water consumption in the YRB is high. The historical maximum in the past 20 years exceeded 80 %. Although agricultural water consumption has continuously declined in recent years, its share remains above 60 %. Additional information on the spatiotemporal patterns of meteorological variables (including precipitation, effective precipitation, and reference crop evapotranspiration), as well as changes in provincial crop irrigation areas in the YRB, is provided in Supplementary material 2 (Text 1; Figs. S1–S3).

2.2. Data sources and preprocessing

To estimate the crop irrigation water requirements, we used meteorological, soil texture, crop distribution and crop growth information data. The meteorological data used (precipitation, temperature, wind speed, etc.) were sourced from the China Regional Surface Meteorological Element Driving Dataset (spatial resolution: 0.1°) published by the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn) from 2000 to 2018, and the Deep Learning Downscaled CMIP6 High-Resolution (0.1°) Daily Near-Surface Meteorological Datasets (spatial resolution: 0.1°) over East Asia (ensemble mean) published by the Science Data Bank (https://www.scidb.cn) from 2019 to 2100. Soil texture data were obtained from the China Soil Texture Spatial Distribution Dataset (spatial resolution converted from 1 km to 0.1°), published by Resource and Environmental Science Data Platform, Chinese Academy of Sciences (https://www.resdc.cn). Crop distribution data were derived from the 1 km resolution National Crop Distribution Dataset for the three major food crops in China (2000–2019) (spatial resolution converted from 1 km to 0.1°) published by the National Ecosystem Science Data Center (http://www.nesdc.org.cn). Crop growth information was collected from various reference materials, including crop production technical guidance from the Ministry of Agriculture and Rural Affairs of the People's Republic of China (https://www.moa.gov.cn/), FAO irrigation and drainage paper 56 (FAO-56; (Allen et al., 1998)), and relevant literature (Chen, 2023; Sacks et al., 2010; Xiao et al., 2013; Liu et al., 2021; Ling et al., 2019; Yao et al., 2011; Zeng et al., 2007; Chen et al., 2018; Ma et al., 2007; Liu and Pereira, 2000; Zhao, 2010a, 2010b). In this study, we considered the location and climate conditions of the YRB, distinguishing the differences between the period from 2001 to 2018 and the three future scenarios. We also defined specific crop phenological stages and crop growth heights (See Table S1 and Table S2 in Supplementary material 1).

For irrigation water resource matching analysis, we used irrigation area fraction, water use and water supply data. Irrigation area fraction data were sourced from the 2000–2020 annual irrigation farmland maps of China (CIrrMap250) published by Zhang et al. (2024), with spatial resolution converted from 250 m to 0.1°. Water use data were obtained from the National Long-term Water Use Dataset of China (NLWUD) published by Zhou et al. (2020). Water supply data from the mainstream of the Yellow River were collected from the monthly water flow dispatching plans of the Yellow River Conservancy Commission, Ministry of Water Resources. (http://yrcc.gov.cn/), covering the period from January 2012 to December 2024 (with data missing for October 2012). These records include the water allocation quotas from the Yellow River's main stream to each province.

2.3. Construction of irrigation water requirement dataset

Due to meteorological data limitations, we developed the irrigation water requirement dataset in two phases. The first phase covers the period from 2001 to 2018, while the second phase extends from 2019 to 2100 and includes three scenarios. To isolate the impact of climate change on irrigation water requirements, we assumed that crop distribution remained unchanged (based on 2019) from 2019 to 2100. Additionally, we considered the effects of climate change on crop phenology. To ensure consistency between the two phases, we corrected the intermediate results of the second phase (See Text S3 of Supplementary material 1).

The irrigation water requirement per unit area (I_r) was derived as the difference between crop water requirement (ET_c) and effective precipitation (P_e):

$$I_{r,i,t} = ET_{c,i,t} - P_{e,t} \tag{1}$$

Where $I_{r,i,t}$ is the irrigation water requirement for crop i on day t (mm), $ET_{c,i,t}$ is the crop water requirement for crop i on day t (mm), and $P_{e,t}$ is the effective precipitation on day t (mm).

The calculation of P_e was based on the method recommended by the U.S. Department of Agriculture's Soil Conservation Service (Smith, 1992; Döll and Siebert, 2002; Liu et al., 2022):

$$P_{e,t} = \begin{cases} \dfrac{P_{d,t}(4.17 - 0.2P_{d,t})}{4.17} & \left(P_e < 8.3\dfrac{mm}{d}\right) \\ 4.17 + 0.1P_{d,t} & \left(P_e \geqslant 8.3\dfrac{mm}{d}\right) \end{cases} \tag{2}$$

Where P_d is the daily actual precipitation on day t (mm).

ET_c was estimated using the single crop coefficient method according to the Food and Agriculture Organization of the United Nations (FAO-56; (Allen et al., 1998)):

$$ET_{c,i,t} = K_{c,i,t} ET_{0,t} \tag{3}$$

Where $K_{c,i,t}$ is the crop coefficient for crop i on day t, $ET_{0,t}$ represents the reference crop evapotranspiration on day t(mm).

ET_0 was calculated with the Penman–Monteith equation recommended by the FAO-56 :

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\dfrac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{4}$$

Where R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G is soil heat flux density (MJ m−2 day−1); γ is the psychrometric constant (kPa °C−1); T is air temperature at 2 m height (°C); u_2 is wind speed at 2 m height (m s^{-1}); e_S is saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); and Δ is the slope of vapor pressure curve (kPa °C^{-1}).

K_c depends on the crop type and its phenological stages, varying with both region and time. FAO-56 provides typical values of K_c for different crops under standard meteorological conditions. Based on these values, we localized the K_c by incorporating regional climate and crop phenological (Table S1 in Supplementary material 1), and other factors. At the same time, we considered the impact of climate change on crop phenology. The growing seasons for each crop were differentiated for the 2001–2018 period and three future scenarios (ssp126, ssp245, ssp585) (Table S2 in Supplementary material 1). Besides, the calculation formula for K_c varies during different stages of crop growth. The specific calculation methods are described in detail in Text 2 of Supplementary material 1.

For comparison with water supply data, we converted the total irrigation water requirement from millimeters to cubic kilometers, while restricting the area to irrigated zones only:

$$IWR_t = \sum\nolimits_1^n I_{r,i,t} A_i Coef_{irr} \tag{5}$$

Where IWR_t is the total irrigation water requirement on day t (km^3), A_i is the area of each grid cell for crop i (km^2), and $Coef_{irr}$ is the irrigation area fraction for the corresponding grid cell (Zhang et al., 2024), with values in the range of [0, 1).

2.4. Construction of supply-side data

Due to the limitations in data availability, we collected data from two different periods. The first period (2001–2013) includes annual actual irrigation water use data, which were used for spatial-scale matching analysis. The second period (2012–2024) includes monthly water diversion data of the Yellow River, which were used for temporal-scale matching analysis.

For the first period, we integrated the water use intensity data from Zhou et al. (2020) to calculate the total irrigation water use for rice, wheat, and maize:

$$WU = \sum\nolimits_1^n WUI_i A_i Coef_{irr} \tag{6}$$

Where WU is the total irrigation water use for the five crops (km^3), and WUI_i is the irrigation water use intensity for crop i (mm). When processing the vector boundaries of the YRB and municipal boundaries, the total irrigation water use at the municipal boundary was distributed proportionally according to the area, with only the water use within the YRB vector boundary being considered.

For the second period, we calculated the total irrigation water allocation for rice, wheat, and maize based on the collected and organized Yellow River main stream dataset:

$$WS = \beta_{avg} W_{yr} \tag{7}$$

$$\beta = \frac{WU}{WU_{total}} \tag{8}$$

Where WS is the total irrigation water supply for the five crops (km^3); W_{yr} is the total allocated water volume from the Yellow River main stream; WU_{total} is the total water use for all sectors, derived from the dataset by Zhou et al. (2020); β is the water use proportion for five crops, and β_{avg} is the multi-year average water use proportion for each municipality within the province.

2.5. Irrigation water supply and requirement matching analysis

In the irrigation water supply and requirement matching analysis, we used *IWR* as the requirement side, and *WU* or *WS* as the supply side. As mentioned in Section 2.4, the use of different datasets and time periods was based on the temporal coverage and resolution of the available data: *IWR* (2001–2013) and *WU* (2001–2013) were used for spatial-scale analysis, while *IWR* (2012–2018 for historical; 2019–2100 for future) and *WS* (2012–2018 for historical; 2019–2024 for future) were used for temporal-scale analysis. It should be noted that WS was assumed to remain constant in the future, which allowed us to assess the future WS-IWR relationship

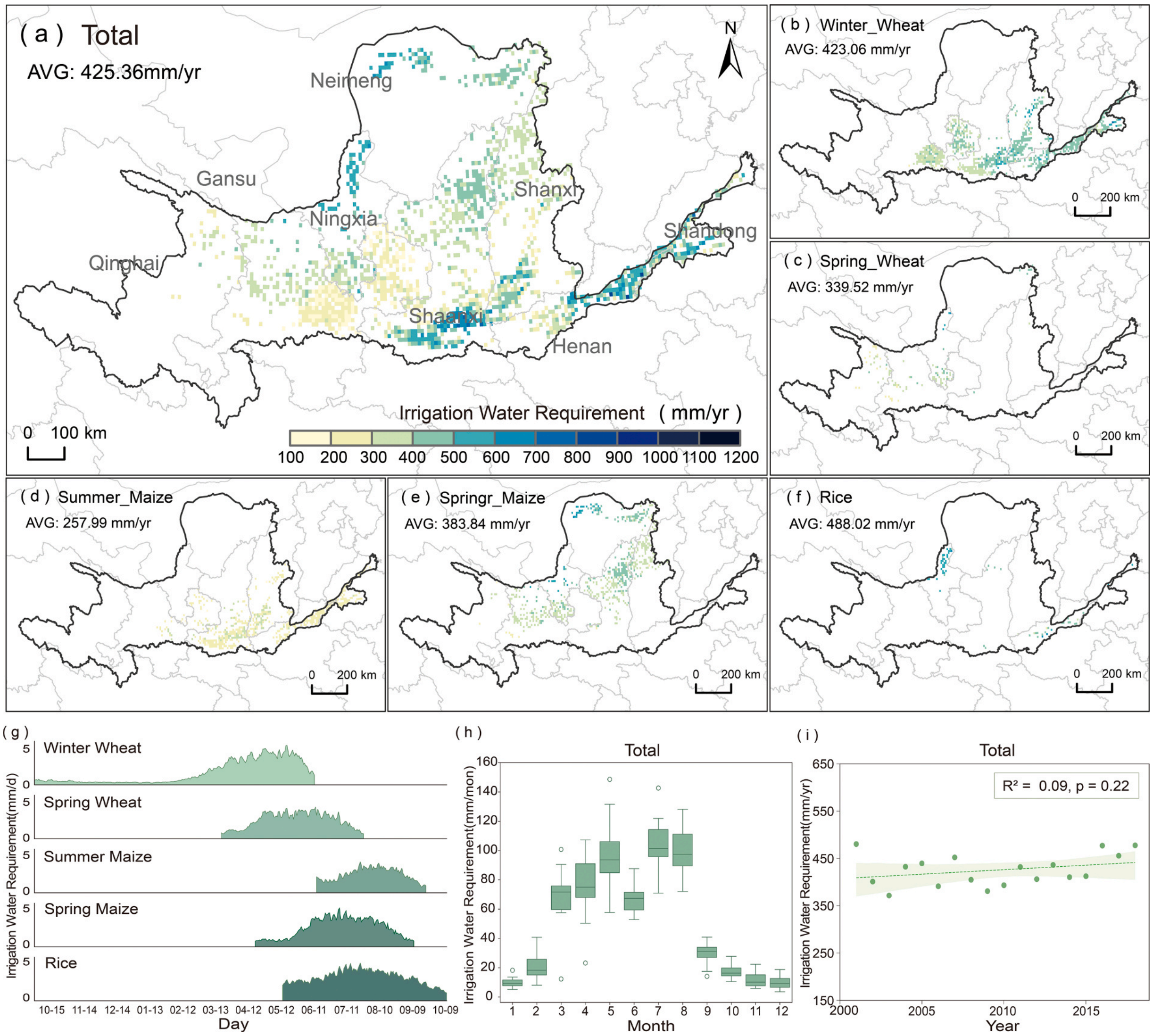

Fig. 2. Spatiotemporal Patterns of Irrigation Water Requirements for Major Crops in the YRB from 2001 to 2018. Spatial Distribution of Total Irrigation Water Requirement (a) and Irrigation Water Requirements for Winter Wheat (b), Spring Wheat (c), Summer Maize (d), Spring Maize(e), and Rice(f). Daily Variation in Irrigation Water Requirements for Each Crop (g; x-axis values are in MM-DD format, e.g., 10–15 = October 15). Monthly Variation in Total Irrigation Water Requirement (h; x-axis 1–12 represents January to December), and Annual Variation (i).

under a scenario in which provincial water allocations remain unchanged.

To compare the *IWR* and *WU* across provinces, we first tested the normality of the *IWR* and *WU* data. For provinces where both datasets conformed to normal distribution, a paired *t*-test was applied to assess significance. For provinces not meeting normality assumptions, the Wilcoxon signed-rank test was used. To compare the seasonal distributions of *IWR* and *WS* across provinces, we first calculated the Wasserstein distance to quantify the magnitude of distribution differences (Panaretos and Zemel, 2019). Then, the Kolmogorov-Smirnov (KS) test was applied to assess the statistical significance of these differences.

3. Results

3.1. Spatiotemporal Patterns of Irrigation Water Requirements from 2001 to 2018

The total irrigation water requirement in the YRB (Fig. 2a) ranges from 163.81 to 663.42 mm/yr (1 %-99 %), with an average of 425.36 mm/yr. The main hotspots of irrigation water requirement are the Ningxia Plain, Hetao Plain, Weihe Plain, and the downstream planting areas. Significant differences exist in the spatial distribution and irrigation water requirements among different crop types. Rice (Fig. 2f) has the highest average irrigation water requirement, at 488.02 mm/yr, with particularly high values in the Ningxia Plain, exceeding 500 mm/yr. Winter wheat (Fig. 2b) follows, with an average of 423.06 mm/yr, and higher water requirements are observed in the lower Fen River region, the central Fenwei Plain, and the plains around the Xiaolangdi Reservoir. Spring maize (Fig. 2e) requires 383.84 mm/yr on average, with higher values found in the Hetao Irrigation Area of Neimeng and the central Yellow River irrigation area in Ningxia. Spring wheat (Fig. 2c) has an average requirement of 339.52 mm/yr, with high values in the northern part of Ningxia and the northeastern corner of the basin's upstream region. Summer maize (Fig. 2d) has the lowest irrigation water requirement, averaging 257.99 mm/yr, with slightly higher requirements in the Fenwei Plain.

The daily variation patterns of irrigation water requirements for each crop are shown in Fig. 2g. For the total irrigation water requirement, two peaks were observed during the year, occurring in March-May and July-August, respectively. These two periods together account for approximately 73 % of the total annual irrigation water requirement, indicating higher water requirements in summer and autumn and lower water requirement in winter and spring. From an interannual perspective (Fig. 2i), the total irrigation water requirement from 2001 to 2018 shows a gradual upward but insignificant trend. The irrigation water requirements for the five crops exhibit slight variation (Fig. S4 in Supplementary material 1), maintaining relative stability amidst fluctuations. Only spring maize shows a significant annual decrease, while the trends for the other four crops, increasing or decreasing, are not substantial.

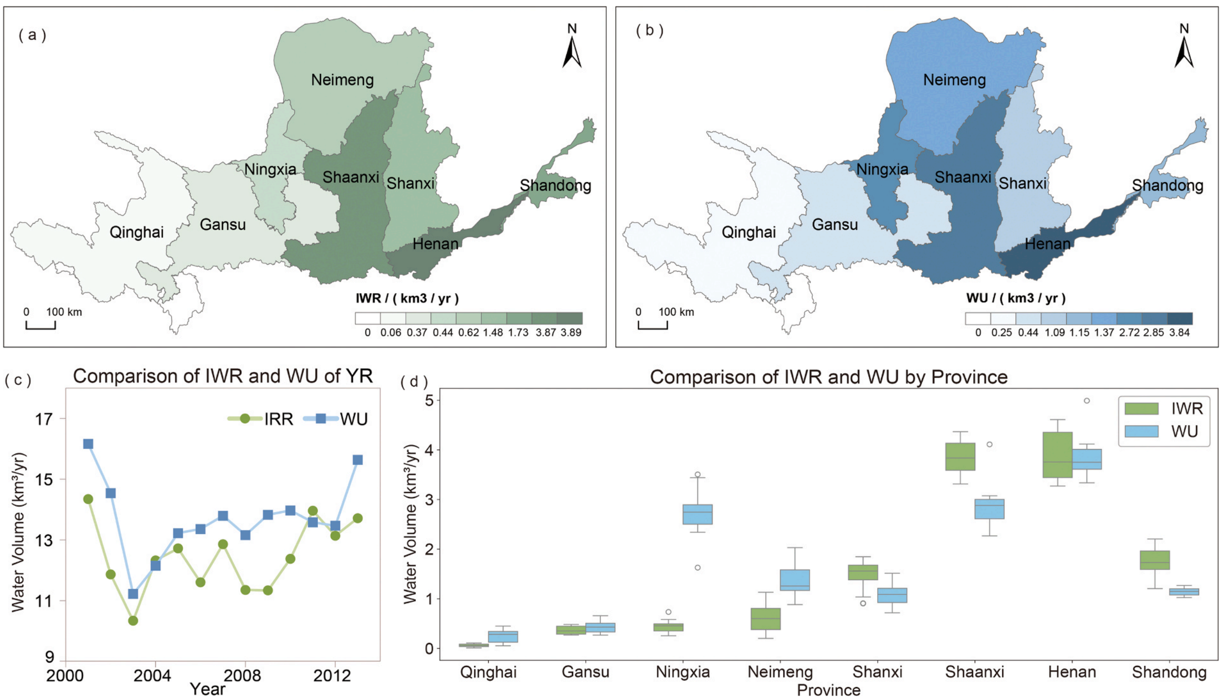

Fig. 3. Comparison of total irrigation water requirement (IWR) and water use (WU) from 2001 to 2013. (a) Multi-year average IWR of each province. (b) Multi-year average WU of each province. (c) Annual variation of IWR and WU in the YRB. (d) Comparison of multi-year IWR and WU of each province.

3.2. Mismatch of irrigation water resources from 2001 to 2018

By comparing the *IWR* and *WU* from 2001 to 2013, we found that their spatial patterns were mismatched (Fig. 3). At the basin scale (Fig. 3c), WU generally exceeded IWR from 2000 to 2013. However, at the provincial level (Figs. 3a, b, d), statistical tests confirmed significant spatial differences between IWR and WU (Table S3 in Supplementary material 1). In the source regions and upper reaches (Qinghai, Gansu, Ningxia, and Neimeng), *IWR* was significantly lower than *WU* ($p < 0.05$). In the middle and lower reaches (Shaanxi, Shanxi, and Shandong), *IWR* was significantly higher than *WU* ($p < 0.001$), except in Henan, where the difference was not statistically significant ($p = 0.635$).

We also observed that the seasonal mismatch between *IWR* and *WS* was widespread across the provinces in the YRB (Fig. 4). In many provinces, *WS*'s peak occurred earlier than *IWR*'s. In Qinghai, *WS* could meet *IWR*. However, the *IWR* peaked from May to June, while *WS* peaked in July when *IWR* was relatively low, indicating a certain degree of seasonal mismatch. In Gansu, Ningxia, and Neimeng, *WS*'s peak occurred from May to July, whereas *IWR* peaked from June to August, showing an obvious seasonal mismatch. In Shanxi, *WS* was generally highest in June, while *IWR* peaked from March to May and from July to August, demonstrating a significant mismatch. In Shaanxi, *WS* had two small peaks in March and July, while *IWR* peaked from June to August. In Henan, March and June were two small peaks for *WS*, but *IWR* peaked from April to May and August, with *IWR* lagging behind *WS*. In Shandong, *WS*'s peak occurred from March to April, while the highest *IWR* was in May, also lagging behind the *WS* peak.

These temporal discrepancies were statistically confirmed by Wasserstein Distance and KS tests (Table S4 in Supplementary material 1). The Wasserstein Distance quantifies differences in the distribution between *WS* and *IWR*, while the KS test assesses the significance of these differences. All provinces exhibited significant differences ($p < 0.05$), confirming the existence of substantial seasonal mismatches between *IWR* and *WS* in the YRB.

3.3. Changes in Irrigation Water Requirements and Supply-Requirement Relationships from 2019 to 2100

From 2019–2100, *IWR* is projected to maintain two distinct intra-annual peaks: from March to May and from July to August, and notable increases are expected in March and July compared to 2001–2018 (Fig. 5a). Additionally, under all future scenarios, the total irrigation water requirement is anticipated to show a significant upward trend over the years (Fig. 5b). When considering individual crops, the *IWR* of winter wheat, summer maize, spring maize, and rice showed significant upward trends over the years under all three scenarios. In contrast, spring wheat exhibited varying patterns. Details are provided in Table 1.

We found that *WS*'peak still occurs earlier than *IWR*'peak from 2019 to 2100 (Fig. 6). These seasonal mismatches remain evident under all future SSP scenarios, as confirmed by the Wasserstein Distance and KS test results (Table S5 in Supplementary material 1). Significant differences ($p < 0.05$) were observed across all provinces and scenarios. Moreover, with the delayed *IWR*'peaks (compared to the 2001–2018 period, Fig. 4) and the increase in *IWR*, the seasonal mismatch is expected to intensify in some provinces. Shaanxi showed the most pronounced mismatch: *WS*'peaks will occur in March and from June to July, while *IWR*'peaks will appear in May and September, resulting in a complete mismatch.

4. Discussion

Our study established an irrigation water requirement dataset for five major food crops in the YRB from 2001 to 2100. We compared and validated the 2001–2018 results with published studies. There was good consistency in evapotranspiration (ET_0) between our results and those of Wang et al. (2022) at the basin scale (Fig. S6 in Supplementary material 1). The province-scale

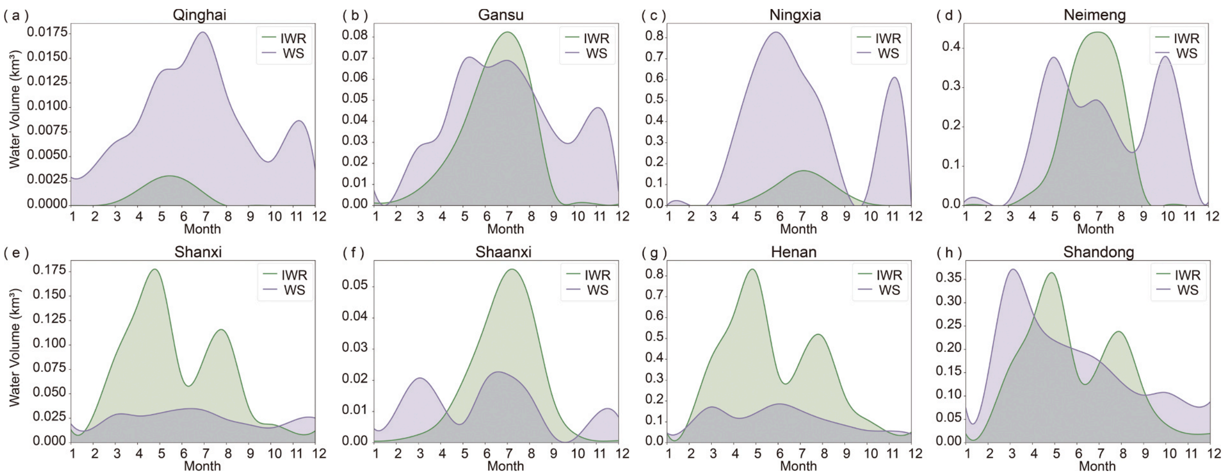

Fig. 4. Comparison of Provincial total irrigation water requirement (IWR) and water supply (WS) from 2012 to 2018. (a) Qinghai; (b) Gansu; (c) Ningxia; (d) Neimeng; (e) Shanxi; (f) Shaanxi; (g) Henan; (h) Shandong.

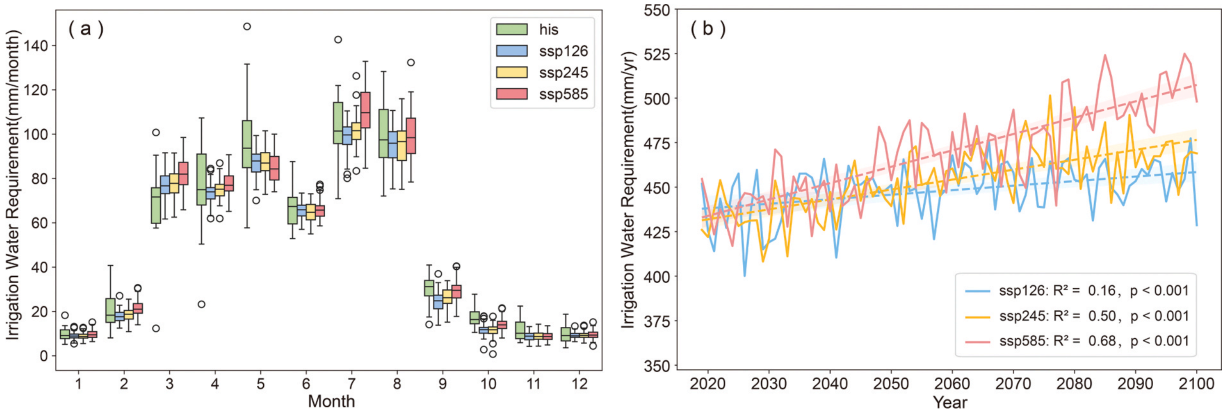

Fig. 5. Temporal Variation of Irrigation Water Requirement from 2019 to 2100. (a) Intra-annual Variation; (b) Inter-annual Variation.

Table 1
Annual variations in *IWR* for five crops under three future scenarios(mm/yr).

Crops	SSP 126	SSP 245	ssp 585
Winter Wheat	0.18**	0.27***	0.32***
Spring Wheat	−0.03	0.01	0.15***
Summer Maize	0.20*	0.44***	0.90***
Spring Maize	0.25***	0.65***	1.03***
Rice	0.51***	0.85***	1.46***

Note *P < 0.05; **P < 0.01; ***P < 0.001.

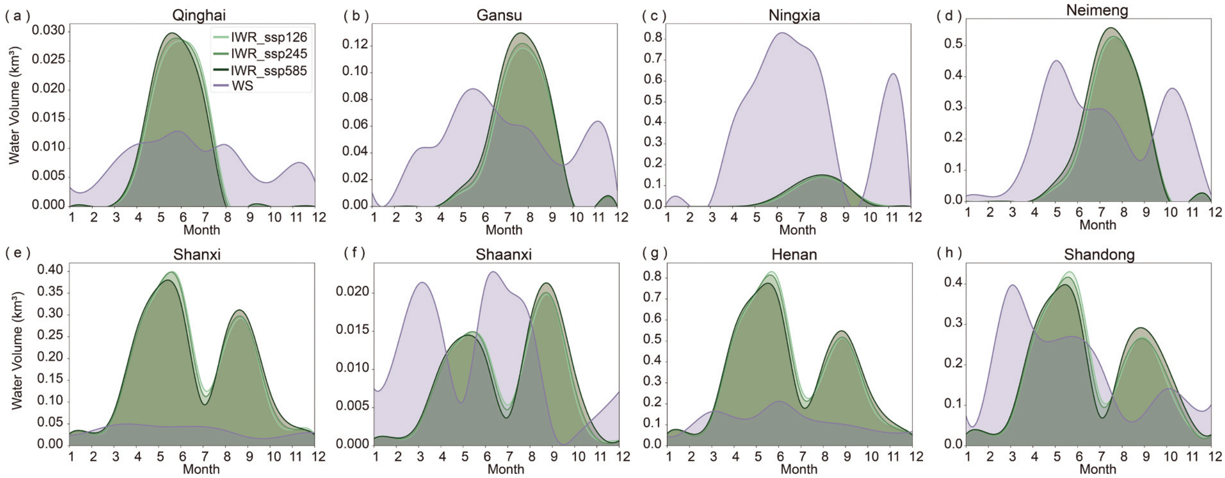

Fig. 6. Comparison of Provincial total irrigation water requirement (IWR) and water supply (WS) from 2019 to 2100. (a) Qinghai; (b) Gansu; (c) Ningxia; (d) Neimeng; (e) Shanxi; (f) Shaanxi; (g) Henan; (h) Shandong.

comparisons (Fig. S7 in Supplementary material 1) indicated high temporal correlations across provinces, with strong consistency in both seasonal and interannual variations. Spatial consistency was relatively lower in certain areas, which may be mainly attributed to differences in data sources: we used gridded reanalysis data, while Wang et al. (2022) employed meteorological station data. In provinces such as Shandong, where stations are sparse within the basin, the two datasets showed lower R^2 values and higher RMSE (Table S6 in Supplementary material 1). Despite these local discrepancies, overall results demonstrate that the ET_0 dataset used in this study is reliable, supporting the accuracy of subsequent calculations. The range of crop water requirement (ET_c) is consistent with those reported in previous studies (Table S7 in Supplementary material 1), while the use of high-resolution data and updated crop coefficients in this study has improved the spatiotemporal resolution of the estimates. This suggests that the irrigation water requirement dataset we constructed from 2001 to 2018 is reliable. The differences in irrigation water requirements among major crops are influenced not only by the spatiotemporal distribution of P_e and ET_0, but also by crop phenology and spatial distribution. For instance, both winter wheat and summer maize are primarily grown in the humid middle and lower reaches, yet their irrigation requirements differ markedly. Winter wheat has a long growing season (October to the following May) that completely misses the summer rainy period, during which ET_0 remains at a moderate level, resulting in high irrigation requirements. In contrast, summer maize grows from June to September, aligning with the rainy season, and thus benefits from abundant P_e that substantially offsets evapotranspiration losses, leading to lower irrigation requirements.

We found that *WU* in the four provinces of the source region and upper reaches exceeds *IWR*, consistent with existing studies. The Qingtongxia and Hetao Irrigation District (Hetao) divert nearly 25 % of the Yellow River's annual runoff (Chen et al., 2003; Ren et al., 2016). Long-term excessive irrigation has led to low water and fertilizer use efficiency and secondary salinization in the upper reaches irrigation districts of the Yellow River (Xu et al., 2013; Ren et al., 2016; Zhang et al., 2016). Meanwhile, *WU* in the provinces of the middle and lower reaches is lower than *IWR*. Due to high upstream water consumption, the lower basin experiences a continuous decline in water discharge. (Xiong et al., 2021; Tian et al., 2019; Piao et al., 2010). This represents a significant spatial mismatch between *WU* and *IWR*. The source region and upper reaches are dominated by spring maize monoculture (Fig. 1), where *IWR* is relatively low, but *WU* often exceeds it. This mismatch is particularly pronounced in Ningxia, where *WU* is much higher than *IWR*. According to Eqs. (5) and (6), this discrepancy stems from the difference between irrigation water use intensity (*WUI*, mm) and irrigation requirement per unit area (I_r, mm). In Ningxia, *WUI* for various crops (Zhou et al., 2020) significantly exceeds their corresponding I_r values. The middle and lower reaches implement a winter wheat-summer maize rotation (Fig. 1), where *IWR* is high but *WU* fails to meet it adequately. This spatial mismatch may constrain agricultural sustainability and regional equity, exacerbating conflicts and competition over water resources between upstream and downstream regions (Hou et al., 2024; Smolenaars et al., 2023). Additionally, a seasonal mismatch exists between *WS* and *IWR*. The administrative water allocation system in the YRB, such as annual water use plans, results in rigid distribution that fails to align with dynamic requirements, prompting provinces to withdraw water in advance to secure quotas (Shen, 2021). However, this static allocation pattern struggles to adapt to the dynamic changes in actual water requirement, leading to inefficiencies. Early *WS* may cause premature reservoir storage and unnecessary evaporation losses (Wang et al., 2024). Some regions are forced to rely on groundwater over-extraction to fill the irrigation gap during water-scarce critical crop growth periods (Lin et al., 2019; Wang et al., 2023; Zhang et al., 2019). This further exacerbates rising irrigation costs, continuous groundwater level decline, and other multidimensional resource depletion (Niazi et al., 2024; Perez et al., 2024; Konikow, 2011). Overall, spatiotemporal mismatches pose challenges to water management, requiring adaptive strategies that flexibly address seasonal requirements and integrate cross-regional coordination. Specifically, we advocate for greater emphasis on institutional "fitness" through flexibility, responsiveness, and anticipatory capacity, rather than merely focusing on how governance can "fit" within a fixed biophysical boundary (Moore et al., 2024). Variations in irrigation requirements across different regions, crops, and seasons should be factored into water resource allocation. This will help ensure adequate water supply during critical crop growth stages and improve the efficiency of resource allocation. Moreover, inter-basin water transfer may play a key role in future water resource allocation (Zhang and Oki, 2024). Implementing the South-to-North Water Diversion Project may be necessary for water scarcity in the YRB and address the requirement.

It is necessary to acknowledge that some uncertainties exist in this study. In the context of future temperature increases and uncertain precipitation patterns (Chai et al., 2022; Gao et al., 2024), we observed a general upward trend in the irrigation water requirement for major crops in the YRB, which aligns with the findings Liu et al. (2022). However, this study does not consider the feedback of the climate system on crop growth. Research has indicated that irrigation water requirement increases without CO2 fertilization, decreasing when CO2 is applied (Elliott et al., 2014). In addition, uncertainty in analyzing the seasonal mismatch between *IWR* and *WS* arises from data coverage and water resource allocation assumptions. The available water supply data only includes the mainstem of the Yellow River, so we trimmed the water requirement dataset based on the Yellow River water allocation and dispatching implementation report (YRCC, 2024, 2015) to standardize the study scope. Due to the lack of monthly water allocation data within and outside the basin, we reasonably assume that the water diverted from the main stream of the Yellow River is only used within the basin, and the water diverted from tributaries is also only used in their small basins. Although *IWR* and *WS* in the mainstem may be overestimated or underestimated in absolute values, this does not affect their seasonal distribution. The conclusion that there is a seasonal mismatch between irrigation water supply and the requirements of YRB remains valid.

5. Conclusions

We reveal the spatiotemporal patterns and mismatches of agricultural irrigation water requirement in the YRB. From 2001–2018, the total annual irrigation water requirement averaged 13.20 km^3 . It is projected to increase significantly under three future climate scenarios (from 2019 to 2100). Spatially, Ningxia Plain, western Hetao Plain, Weihe Plain, and downstream croplands exhibit higher irrigation water requirements. Temporally, two peaks in irrigation water requirement emerge within a year: from March to May and from July to August. *WU* was sufficient to meet *IWR* in the source regions and upper reaches, while the mid and lower reaches faced shortfalls. Across provinces, *WS*' peak generally occurred earlier than *IWR*' peak. In the future, seasonal mismatches between *WS* and *IWR* will persist, and may intensify due to the delayed peak of *IWR* and its increase. These findings underscore the urgent need for adaptive water governance in the YRB to tackle emerging challenges.

CRediT authorship contribution statement

Xutong Wu: Funding acquisition, Writing – review & editing. **Peng Chen:** Data curation, Methodology, Writing – review & editing. **Shuai Wang:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Shuang Song:** Conceptualization, Data curation, Funding acquisition, Writing – review & editing. **Yueman Hou:** Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft.

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.

Acknowledgments

This research has been supported by the National Natural Science Foundation of China (grant no. U2243601, 42401126 and 42201306) and the Fundamental Research Funds for the Central Universities.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102715.

Data availability

Data will be made available on request.

References

Allen, R., Pereira, L., Raes, D., Smith, M., 1998. FAO Irrigation and drainage paper No. 56. Food and Agriculture Organization of the United Nations, Rome, pp. 26–40.
Chai, Y., Yue, Y., Slater, L.J., Yin, J., Borthwick, A.G.L., Chen, T., Wang, G., 2022. Constrained CMIP6 projections indicate less warming and a slower increase in water availability across Asia. Nat. Commun. 13, 4124. https://doi.org/10.1038/s41467-022-31782-7.
Chen, X., 2023. Tracking the spatio-temporal change of the main food crop planting structure in the Yellow River Basin over 2001–2020. Comput. Electron. Agric.
Chen, Yiping, Fu, Bojie, Zhao, Yan, Wang, Kaibo, Zhao, Meng M., 2020. Sustainable development in the Yellow River Basin: issues and strategies. J. Clean. Prod. 263, 121223. https://doi.org/10.1016/j.jclepro.2020.121223.
Chen, J., He, D., Cui, S., 2003. The response of river water quality and quantity to the development of irrigated agriculture in the last 4 decades in the Yellow River Basin, China. Water Resour. Res. 39. https://doi.org/10.1029/2001WR001234.
Chen, F., Yin, X., Zhao, Q., Bi, C., Xian, W., Li, Jingling, Sun, Gongchen, Zhu, Wenyin, Zhang, Shiyong, 2018. Technical regulations for high-yield and high-quality direct seeding rice cultivation in saline-alkali land of the Yellow River Delta. North. Rice 48, 37–39. https://doi.org/10.16170/j.cnki.1673-6737.2018.04.010.
Chiarelli, D.D., Passera, C., Rosa, L., Davis, K.F., D'Odorico, P., Rulli, M.C., 2020. The Green and blue crop water requirement WATNEEDS model and its global gridded outputs. Sci. Data 7, 273. https://doi.org/10.1038/s41597-020-00612-0.
Döll, P., Siebert, S., 2002. Global modeling of irrigation water requirements. Water Resour. Res. 38, 8-1–8-10. https://doi.org/10.1029/2001WR000355.
Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc. Natl. Acad. Sci. 111, 3239–3244. https://doi.org/10.1073/pnas.1222474110.
Fu, B., Wang, S., Liu, Y., Liu, J., Liang, W., Miao, C., 2017. Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the loess plateau of China. Annu. Rev. Earth Planet. Sci. 45, 223–243. https://doi.org/10.1146/annurev-earth-063016-020552.
Gao, X., Hao, Q., Wang, L., Song, Y., Ge, J., Wu, H., Xu, B., Han, L., Fu, Y., Wu, X., Deng, C., Guo, Z., 2024. Changes in monsoon precipitation in east Asia under a 2°C interglacial warming. Sci. Adv. 10, eadm7694. https://doi.org/10.1126/sciadv.adm7694.
Giordano, V., Tuninetti, M., Laio, F., 2023. Efficient agricultural practices in Africa reduce crop water footprint despite climate change, but rely on blue water resources. Commun. Earth Environ. 4, 1–12. https://doi.org/10.1038/s43247-023-01125-5.
Hou, Y., Zhao, G., Liu, Y., Li, X., 2024. Spatial adaptation patterns and coordinated development of water-energy-food complex system in the Yellow River Basin. Sci. Rep. 14, 31241. https://doi.org/10.1038/s41598-024-82601-6.
Jian, S., Pei, Y., Zhu, T., Yu, X., 2023. Spatiotemporal change and attribution analysis of future runoff on the Yellow River Basin of China. J. Hydrol. Reg. Stud. 49, 101494. https://doi.org/10.1016/j.ejrh.2023.101494.
Konikow, L.F., 2011. Contribution of global groundwater depletion since 1900 to sea-level rise. Geophys. Res. Lett. 38. https://doi.org/10.1029/2011GL048604.
Li, X., Zhang, X., Wang, S., 2021. Managing conflicts and equitability in hierarchical decision making for water resources planning under fuzzy uncertainty: a case study of Yellow River, China. J. Hydrol. Reg. Stud. 38, 100963. https://doi.org/10.1016/j.ejrh.2021.100963.
Lin, M., Biswas, A., Bennett, E.M., 2019. Spatio-temporal dynamics of groundwater storage changes in the Yellow River Basin. J. Environ. Manag. 235, 84–95. https://doi.org/10.1016/j.jenvman.2019.01.016.
Ling, X.-X., Zhang, Z.-L., Zhai, J.-Q., Ye, S.-C., Huang, J.-L., 2019. A review for impacts of climate change on rice production in China. Acta Agron. Sin. 45, 323. https://doi.org/10.3724/SP.J.1006.2019.82044.
Liu, Yanqi, Lin, Y., Huo, Z., Zhang, C., Wang, C., Xue, J., Huang, G., 2022. Spatio-temporal variation of irrigation water requirements for wheat and maize in the Yellow River Basin, China, 1974–2017. Agric. Water Manag. 262, 107451. https://doi.org/10.1016/j.agwat.2021.107451.
Liu, Y., Pereira, L.S., 2000. Validation of the FAO recommended method for calculating crop coefficients. Trans. Chin. Soc. Agric. Eng. 26, 30.
Liu, Yang, Yang, Y., Wang, Z., An, S., 2022. Quantifying water provision service supply, demand, and spatial flow in the Yellow River Basin. Sustainability 14, 10093. https://doi.org/10.3390/su141610093.
Liu, Y., Zhang, J., Pan, T., Ge, Q., 2021. Assessing the adaptability of maize phenology to climate change: the role of anthropogenic-management practices. J. Environ. Manag. 293, 112874. https://doi.org/10.1016/j.jenvman.2021.112874.
Luo, Y., Zhang, Z., Li, Z., Chen, Y., Zhang, L., Cao, J., Tao, F., 2020. Identifying the spatiotemporal changes of annual harvesting areas for three staple crops in China by integrating multi-data sources. Environ. Res. Lett. 15, 074003. https://doi.org/10.1088/1748-9326/ab80f0.
Lutz, A.F., Immerzeel, W.W., Siderius, C., Wijngaard, R.R., Nepal, S., Shrestha, A.B., Wester, P., Biemans, H., 2022. South asian agriculture increasingly dependent on meltwater and groundwater. Nat. Clim. Chang 12, 566–573. https://doi.org/10.1038/s41558-022-01355-z.
Ma, G., Xue, J., Lu, H., Zhang, R., Tai, S., Ren, J., 2007. Effects of sowing date and plant density on physiological parameters of summer maize population in guanzhong irrigation district. Chin. J. Appl. Ecol. 18, 1247–1253. https://doi.org/10.13287/j.1001—9332.2007.0210.

Ma, Xuening, Zhang, Mingjun, Wang, Shengjie, Ma, Qian, Pan, Shukun, 2012. Evaporation paradox in the Yellow River Basin. Acta Geogr. Sin. 67, 645–656. https://doi.org/10.11821/xb201205007.

McDermid, S.S., 2024. Agricultural water demand is taxing regional water supplies. Nat. Water 2, 225–227. https://doi.org/10.1038/s44221-024-00215-8.

Mehta, P., Siebert, S., Kummu, M., Deng, Q., Ali, T., Marston, L., Xie, W., Davis, K.F., 2024. Half of twenty-first century global irrigation expansion has been in water-stressed regions. Nat. Water 2, 254–261. https://doi.org/10.1038/s44221-024-00206-9.

Mekonnen, M.M., Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity. Sci. Adv. 2, e1500323. https://doi.org/10.1126/sciadv.1500323.

Moore, M.-L., Wang-Erlandsson, L., Bodin, Ö., Enqvist, J., Jaramillo, F., Jónás, K., Folke, C., Keys, P., Lade, S.J., Mancilla Garcia, M., Martin, R., Matthews, N., Pranindita, A., Rocha, J.C., Vora, S., 2024. Moving from fit to fitness for governing water in the Anthropocene. Nat. Water 2, 511–520. https://doi.org/10.1038/s44221-024-00257-y.

Mrad, A., Katul, G.G., Levia, D.F., Guswa, A.J., Boyer, E.W., Bruen, M., Carlyle-Moses, D.E., Coyte, R., Creed, I.F., van de Giesen, N., Grasso, D., Hannah, D.M., Hudson, J.E., Humphrey, V., Iida, S., Jackson, R.B., Kumagai, T., Llorens, P., Michalzik, B., Nanko, K., Peters, C.A., Selker, J.S., Tetzlaff, D., Zalewski, M., Scanlon, B.R., 2020. Peak grain forecasts for the US high plains amid withering waters. Proc. Natl. Acad. Sci. 117, 26145–26150. https://doi.org/10.1073/pnas.2008383117.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257. https://doi.org/10.1038/nature11420.

Niazi, H., Wild, T.B., Turner, S.W.D., Graham, N.T., Hejazi, M., Msangi, S., Kim, S., Lamontagne, J.R., Zhao, M., 2024. Global peak water limit of future groundwater withdrawals. Nat. Sustain 7, 413–422. https://doi.org/10.1038/s41893-024-01306-w.

Panaretos, V.M., Zemel, Y., 2019. Statistical aspects of wasserstein distances. Annu. Rev. Stat. Appl. 6, 405–431. https://doi.org/10.1146/annurev-statistics-030718-104938.

Peng, J., Liu, T., Chen, J., Li, Z., Ling, Y., De Wulf, A., De Maeyer, P., 2023. The conflicts of agricultural water supply and demand under climate change in a typical arid land watershed of Central Asia. J. Hydrol. Reg. Stud. 47, 101384. https://doi.org/10.1016/j.ejrh.2023.101384.

Perez, N., Singh, V., Ringler, C., Xie, H., Zhu, T., Sutanudjaja, E.H., Villholth, K.G., 2024. Ending groundwater overdraft without affecting food security. Nat. Sustain. 7, 1007–1017. https://doi.org/10.1038/s41893-024-01376-w.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T., Fang, J., 2010. The impacts of climate change on water resources and agriculture in China. Nature 467, 43–51. https://doi.org/10.1038/nature09364.

Qi, X., Feng, K., Sun, L., Zhao, D., Huang, X., Zhang, D., Liu, Z., Baiocchi, G., 2022. Rising agricultural water scarcity in China is driven by expansion of irrigated cropland in water scarce regions. One Earth 5, 1139–1152. https://doi.org/10.1016/j.oneear.2022.09.008.

Ren, D., Xu, X., Hao, Y., Huang, G., 2016. Modeling and assessing field irrigation water use in a canal system of hetao, upper Yellow River Basin: application to maize, sunflower and watermelon. J. Hydrol. 532, 122–139. https://doi.org/10.1016/j.jhydrol.2015.11.040.

Rosa, L., Chiarelli, D.D., Rulli, M.C., Dell'Angelo, J., D'Odorico, P., 2020. Global agricultural economic water scarcity. Sci. Adv. 6, eaaz6031. https://doi.org/10.1126/sciadv.aaz6031.

Sacks, W.J., Deryng, D., Foley, J.A., Ramankutty, N., 2010. Crop planting dates: an analysis of global patterns. Glob. Ecol. Biogeogr. 19, 607–620. https://doi.org/10.1111/j.1466-8238.2010.00551.x.

Scanlon, B.R., Faunt, C.C., Longuevergne, L., Reedy, R.C., Alley, W.M., McGuire, V.L., McMahon, P.B., 2012. Groundwater depletion and sustainability of irrigation in the US high plains and central valley. Proc. Natl. Acad. Sci. 109, 9320–9325. https://doi.org/10.1073/pnas.1200311109.

Shen, D., 2021. Water resource allocation and regulation in Yellow River Basin. In: Shen, D. (Ed.), Water Resources Management of the People's Republic of China: Framework, Reform and Implementation. Springer International Publishing, Cham, pp. 291–306. https://doi.org/10.1007/978-3-030-61931-2_14.

Smith, Martin, 1992. CROPWAT – A Computer Program for Irrigation Planning and Management. Food and Agriculture Organization of the United Nations.

Smolenaars, W.J., Sommerauer, W.J.-W., van der Bolt, B., Jamil, M.K., Dhaubanjar, S., Lutz, A., Immerzeel, W., Ludwig, F., Biemans, H., 2023. Spatial adaptation pathways to reconcile future water and food security in the Indus river basin. Commun. Earth Environ. 4, 1–12. https://doi.org/10.1038/s43247-023-01070-3.

Song, S., Wen, H., Wang, S., Wu, X., Cumming, G.S., Fu, B., 2024. Quantifying the effects of institutional shifts on water governance in the Yellow River Basin: a social-ecological system perspective. J. Hydrol. 629, 130638. https://doi.org/10.1016/j.jhydrol.2024.130638.

Tian, S., Xu, M., Jiang, E., Wang, G., Hu, H., Liu, X., 2019. Temporal variations of runoff and sediment load in the upper Yellow River, China. J. Hydrol. 568, 46–56. https://doi.org/10.1016/j.jhydrol.2018.10.033.

Wang, S., Fu, B., Bodin, Ö., Liu, J., Zhang, M., Li, X., 2019. Alignment of social and ecological structures increased the ability of river management. Sci. Bull. 64, 1318–1324.

Wang, F., Lai, H., Li, Y., Feng, K., Tian, Q., Guo, W., Qu, Y., Yang, H., 2023. Spatio-temporal evolution and teleconnection factor analysis of groundwater drought based on the GRACE mascon model in the Yellow River Basin. J. Hydrol. 626, 130349. https://doi.org/10.1016/j.jhydrol.2023.130349.

Wang, M., Shi, W., 2024. The annual dynamic dataset of high-resolution crop water use in China from 1991 to 2019. Sci. Data 11, 1373. https://doi.org/10.1038/s41597-024-04185-0.

Wang, Y., Wang, S., Zhao, W., Liu, Y., 2022. The increasing contribution of potential evapotranspiration to severe droughts in the Yellow River Basin. J. Hydrol. 605, 127310. https://doi.org/10.1016/j.jhydrol.2021.127310.

Wang, H., Yang, Q., Li, S., Hao, W., Mu, H., Si, C., Ma, H., 2024. Estimation of evaporation loss from an irrigation reservoir in arid region using effective isotopic fractionation method. Irrig. Sci. https://doi.org/10.1007/s00271-024-00995-7.

Wisser, D., Frolking, S., Douglas, E.M., Fekete, B.M., Vörösmarty, C.J., Schumann, A.H., 2008. Global irrigation water demand: variability and uncertainties arising from agricultural and climate data sets. Geophys. Res. Lett. 35. https://doi.org/10.1029/2008GL035296.

Wu, X., Yan, Z., Yang, H., Wang, S., Zhang, H., Shen, Y., Song, S., Liu, Y., Guo, Y., Yang, D., Fu, B., 2025. Ecological restoration in the Yellow River Basin enhances hydropower potential. Nat. Commun. 16, 2566. https://doi.org/10.1038/s41467-025-57891-7.

Xiao, D., Tao, F., Liu, Y., Shi, W., Wang, M., Liu, F., Zhang, S., Zhu, Z., 2013. Observed changes in winter wheat phenology in the north China plain for 1981–2009. Int J. Biometeorol. 57, 275–285. https://doi.org/10.1007/s00484-012-0552-8.

Xiong, L., Xu, X., Engel, B., Huang, Q., Huo, Z., Xiong, Y., Han, W., Huang, G., 2021. Modeling agro-hydrological processes and analyzing water use in a super-large irrigation district (Hetao) of arid upper Yellow River Basin. J. Hydrol. 603, 127014. https://doi.org/10.1016/j.jhydrol.2021.127014.

Xu, X., Huang, G., Sun, C., Pereira, L.S., Ramos, T.B., Huang, Q., Hao, Y., 2013. Assessing the effects of water table depth on water use, soil salinity and wheat yield: searching for a target depth for irrigated areas in the upper Yellow River Basin. Agric. Water Manag. 125, 46–60. https://doi.org/10.1016/j.agwat.2013.04.004.

Yao, Y., Wang, R., Yang, J., Xiao, G., Zhang, X., 2011. Impacts of climate change on the growth and development of spring wheat in the semi-arid region of the loess plateau: a case study of Dingxi, Gansu. Acta Ecol. Sin. 31, 4225–4234.

YRCC, 2015. 2014-2015 Yellow River water allocation and dispatching implementation report.

YRCC, 2024. 2023-2024 Yellow River water allocation and dispatching implementation report.

Zeng, L., Wei, X., Yang, G., Lu, Y., Liu, Q., Liu, W., 2007. Effects of different cultivation methods on rice growth and yield in the Yellow River irrigation district of ningxia. J. Crops 57–59. https://doi.org/10.16035/j.issn.1001-7283.2007.04.021.

Zhang, A., Gao, J., Liu, R., Zhang, Q., Chen, Z., Yang, S., Yang, Z., 2016. Using side-dressing technique to reduce nitrogen leaching and improve nitrogen recovery efficiency under an irrigated rice system in the upper reaches of Yellow River Basin, northwest China. J. Integr. Agric. 15, 220–231. https://doi.org/10.1016/S2095-3119(14)60952-7.

Zhang, J., Guan, K., Peng, B., Pan, M., Zhou, W., Jiang, C., Kimm, H., Franz, T.E., Grant, R.F., Yang, Y., Rudnick, D.R., Heeren, D.M., Suyker, A.E., Bauerle, W.L., Miner, G.L., 2021. Sustainable irrigation based on co-regulation of soil water supply and atmospheric evaporative demand. Nat. Commun. 12, 5549. https://doi.org/10.1038/s41467-021-25254-7.

Zhang, C.Y., Oki, T., 2024. Water transfer contributes to water resources management: crisis mitigation for future water allocation in the Yellow River basin. iScience 27. https://doi.org/10.1016/j.isci.2024.110586.

Zhang, F., Wu, Z., Di, D., Wang, H., 2023. Water resources allocation based on water resources supply-demand forecast and comprehensive values of water resources. J. Hydrol. Reg. Stud. 47, 101421. https://doi.org/10.1016/j.ejrh.2023.101421.
Zhang, K., Xie, X., Zhu, B., Meng, S., Yao, Y., 2019. Unexpected groundwater recovery with decreasing agricultural irrigation in the Yellow River Basin. Agric. Water Manag. 213, 858–867. https://doi.org/10.1016/j.agwat.2018.12.009.
Zhang, L., Xie, Y., Zhu, X., Ma, Q., Brocca, L., 2024. CIrrMap250: annual maps of China's irrigated cropland from 2000 to 2020 developed through multisource data integration. Earth Syst. Sci. Data 16, 5207–5226. https://doi.org/10.5194/essd-16-5207-2024.
Zhao, Guangcai, 2010b. Regionalization of wheat cultivation in China (Part II). J. Triticeae Crops 30, 1140–1147.
Zhao, Guangcai, 2010a. Regionalization of wheat cultivation in China (Part I). J. Triticeae Crops 30, 886–895.
Zhou, F., Bo, Y., Ciais, P., Dumas, P., Tang, Q., Wang, X., Liu, J., Zheng, C., Polcher, J., Yin, Z., Guimberteau, M., Peng, S., Ottle, C., Zhao, X., Zhao, J., Tan, Q., Chen, L., Shen, H., Yang, H., Piao, S., Wang, H., Wada, Y., 2020. Deceleration of China's human water use and its key drivers. Proc. Natl. Acad. Sci. U. S. A. 117, 7702–7711. https://doi.org/10.1073/pnas.1909902117.
Zhuo, L., Mekonnen, M.M., Hoekstra, A.Y., Wada, Y., 2016. Inter- and intra-annual variation of water footprint of crops and blue water scarcity in the Yellow River Basin (1961–2009). Adv. Water Resour. 87, 29–41. https://doi.org/10.1016/j.advwatres.2015.11.002.