

We sincerely thank the reviewer for the positive evaluation of our manuscript and for providing the opportunity to revise it. We have carefully considered the comments raised by the reviewer. We hope that the revised manuscript now meets the quality standards for publication. Detailed responses to the review comments are provided below (blue text indicates our responses and black text indicates the original comments).

Specific Comments

Comment 1: This study adopts multiple methods, but the methodology appears somewhat overloaded and fragmented. It is recommended to briefly introduce the Data in this section and present the detailed information in the form of supplementary materials or appendices. Also, a flowchart is suggested here to clearly illustrate the integration of the adopted methods. Furthermore, the descriptions of the design of the GSFLOW model and the surrogate model are insufficient, and detailed information (e.g. parameters and variables for the surrogate model) is needed.

Response: Thank you for this important suggestion. We have revised and supplemented the methodology section as follows.

(1) We have added a schematic workflow in Section 3 “Methods” of the revised manuscript. The figure illustrates the complete processes, including input of basic data, coupled surface-groundwater model simulation, surrogate model training, NSGA-III multi-objective optimization, and decision support. It shows the logical relationships among the different modules.

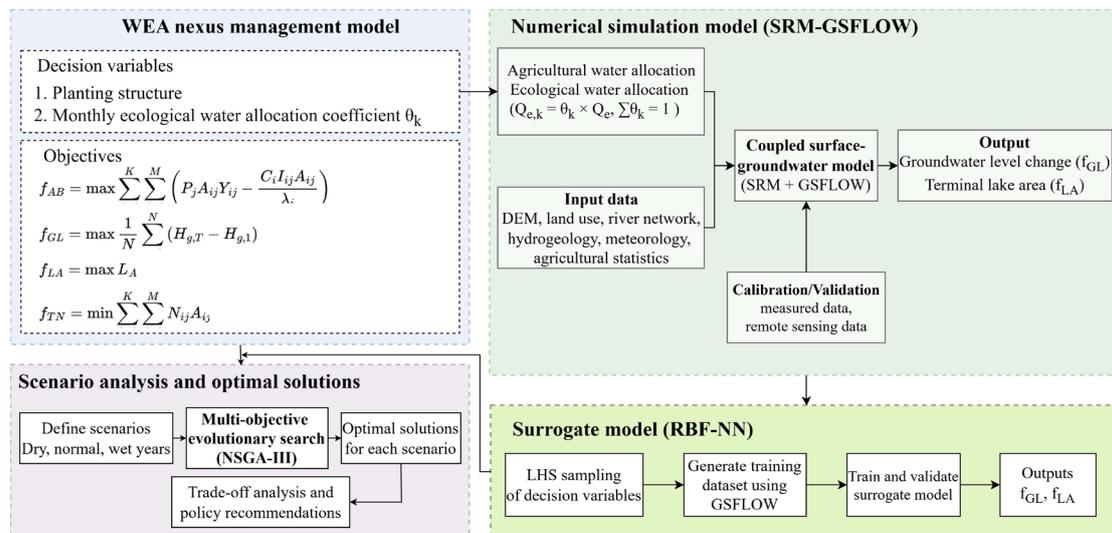


Figure R1. Framework of the multi-objective simulation - optimization for the WEA nexus management.

(2) The data section has been streamlined and structurally optimized. In the revised manuscript, the main text provides only a brief overview of the types of data used, their primary sources, and their roles in the study. The detailed information on the datasets, including sources, spatial and temporal resolutions, and specific applications and data processing procedures, as well as Table 1 from the original manuscript, have all been moved to the Supplementary Materials. The revised Section 2.2 (Data) and the dataset descriptions in the Supplementary Materials are provided below.

Revised text

2.2 Data

The datasets used in this research encompass topography, land use, climate, hydrogeology, and socio-economic information, with a primary temporal coverage from 2002 to 2021. Snow cover information was obtained from the High Asia MODIS daily snow cover fraction product developed by Qiu and Wang (2020). This dataset, derived using the MODIS Normalized Difference Snow Index (NDSI), offers daily data at a spatial resolution of 500 m and serves as a critical input for the snowmelt runoff model (SRM). Terrain-related information was sourced from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM), which has a spatial resolution of 30 m (NASA/METI, 2019). These elevation data were used to extract terrain attributes, including slope, aspect, and river networks.

Land use, vegetation, and soil property data were obtained from multiple sources. Land cover information was obtained from the FROM-GLC dataset (Gong et al., 2013), soil properties were derived from the Harmonized World Soil Database (Wieder et al., 2014), and vegetation attributes were derived from the Vegetation Map of China (Li et al., 2017). Collectively, these datasets provided key inputs for simulating land surface processes and parameterizing soil-related processes in the coupled model.

Hydrogeological conditions were primarily derived from borehole data and regional hydrogeological maps reported by Li et al. (2003). Key parameters, including hydraulic conductivity and specific yield, were assigned based on dominant lithological units.

Meteorological forcing for the coupled surface water-groundwater model consisted of precipitation and temperature (maximum and minimum), which were obtained from the ERA5 reanalysis dataset (Hersbach et al., 2020). Model calibration and validation for the groundwater component relied on monthly groundwater level

measurements from 139 monitoring wells distributed throughout the study area (Xue et al., 2024).

Daily streamflow records from five representative hydrological stations within the Tarim River Basin (2002-2021) were used to calibrate surface runoff simulations and model parameters.

To further evaluate the groundwater simulations of the GSFLOW model, terrestrial water storage anomaly (TWSA) data from the GRACE and GRACE-FO satellite missions (Save et al., 2016; Save, 2024) were used for model validation. In addition, the coupled model was cross-validated using evapotranspiration (GLEAM) (Martens et al., 2017) and soil moisture (Chinese Soil Moisture Dataset) (Mao, 2021; Meng et al., 2021). A comprehensive summary of all datasets employed in this study is provided in Supplementary Table S1.

Socio-economic data were primarily collected from the China Statistical Yearbook (National Bureau of Statistics, 2002-2021), Xinjiang Water Resources Bulletin (Xinjiang Water Resources Department, 2002-2021), and the National Agricultural Product Cost-Benefit Compilation together with annual crop price statistics (Ministry of Agriculture and Rural Affairs of Xinjiang, 2002-2025). These datasets provide information on crop planting areas, yields, and fertilizer and pesticide application rates.

Supplementary Materials

S1 Data sources and preprocessing

This section provides detailed information on the datasets used in this study, including their sources, spatial and temporal resolutions, and specific applications, supplementing the brief description in Section 2.2 (Data).

The datasets employed in this study primarily include meteorological forcing data, remote sensing products, hydrological observations, and model validation data. Surface runoff and snowmelt runoff data were obtained from the GLDAS-2.1 Noah model product, spatially downscaled to a $2\text{ km} \times 2\text{ km}$ resolution, and further aggregated to daily values to drive the GSFLOW model. Meteorological variables, including precipitation, daily maximum temperature, and daily minimum temperature, were derived from the ERA5 reanalysis dataset and similarly downscaled for use as model inputs.

GRACE data were obtained from the RL06 Mascon Level-3 product released by the Center for Space Research (CSR) at the University of Texas at Austin, covering the

period from April 2002 to December 2021. Missing monthly values were filled using cubic spline interpolation. For the gap between the GRACE and GRACE-FO missions (July 2017 to May 2018), terrestrial water storage reconstruction data developed by Zhong et al. (2019, 2020) were used to ensure a continuous time series. Monthly terrestrial water storage change (TWSC) was calculated from the TWSA series as follows:

$$TWSC(t) = TWSA(t) - TWSA(t-1)$$

where $TWSC(t)$ represents the change in terrestrial water storage (mm) during month t , and $TWSA(t)$ represents the corresponding storage anomaly.

Detailed information on the spatial and temporal resolutions of these datasets and their specific applications is provided in Supplementary Table S1.

Table S1. Data for the coupled hydrology-agriculture optimization framework.

Data	Dataset / Source	Spatial & Temporal Resolution	Usage
Snow cover	High Asia MODIS daily snow cover fraction dataset	500 m Daily	Model input
Climate forcing	ERA5 reanalysis	0.25°×0.25° hourly	Model input
Topography	ASTER GDEM	30 m	Model input
Hydrogeology	hydrogeological maps, borehole data	Site-specific	Model input
Land surface	FROM-GLC, HWSD. Vegetation Map of China,	Dataset-specific	Model input
Socio-economic data	XSB, XWRB, NAPCBC & ARAX	Annual	Model input
Groundwater level	Monitoring wells	Monthly	Model validation
Terrestrial water storage changes	GRACE/GRACE-FO (CSR RL06 Mascon)	0.25°×0.25° month	Model validation
Evapotranspiration	GLEAM	0.25°×0.25° monthly	Model validation
Soil moisture	Soil Moisture in China dataset	0.05°×0.05° monthly	Model validation

(3) In Section 3.1.1, a brief introduction to the GSFLOW model has been added.

“GSFLOW is a physically based distributed coupled hydrological modeling system that integrates the PRMS (Precipitation-Runoff Modeling System) surface hydrological process module with the MODFLOW groundwater flow module to simulate surface water-groundwater interactions at the watershed scale (Markstrom et al., 2008). The model is capable of simulating key hydrological processes such as precipitation, evapotranspiration, infiltration, surface runoff, groundwater recharge, and stream-

aquifer exchange.”

(4) In Section 3.3 “Surrogate Model Construction and Validation,” additional details regarding the construction of the surrogate model have been provided.

“The input variables of the surrogate model are the decision variables to be optimized. Specifically, they include the planting areas of six major crops (cotton, maize, oil crops, vegetables, melons, and fruits) across seven irrigation zones, as well as the allocation coefficients of ecological water use during key months (May-September), resulting in a total of 47 decision variables. The output variables of the surrogate model consist of two hydrological variables simulated by the coupled hydrological model (GSFLOW), namely the change in the average groundwater depth in the study area and the area of the terminal lake. To construct the surrogate model, Latin hypercube sampling was first applied to generate samples within the input variable space. Each sample set was then used as input to the GSFLOW model to obtain the corresponding outputs, thereby forming an input-output dataset. The dataset was subsequently randomly divided into a training set (70%) and a test set (30%). The training set was used to train the radial basis function neural network (RBF-NN), while the testing set was used to evaluate the predictive accuracy and generalization capability of the surrogate model.”

Comment 2: The findings of this study need to be further discussed to enhance the value of the manuscript. It is recommended to discuss the advantages and limitations of the multi-objective optimization framework used in this study compared with previous research (e.g. for single methods or combinations of two methods). It would greatly increase the significance of the study, if quantitative comparison can be presented. The discussion could also be strengthened by addressing how the findings of this study could be applied to other regions. This may involve identifying which of the datasets used has the greatest impact on the results, as well as considering how errors from different datasets could limit the applicability of the methodology in other areas.

Response: Thank you for the reviewer’s comment. We have added the following discussion in Section 5.1 “Implications for WEA Synergistic Management and Adaptation in Arid Basin Regions.”

“The multi-objective optimization framework developed in this study, using the mainstream of the Tarim River as a representative case, provides a comprehensive analytical approach for coordinating water-ecosystem-agriculture (WEA) conflicts. Compared to previous studies in this region that primarily focused on single or dual objectives, this framework integrates a coupled surface water-groundwater model with multi-objective decision-making methods, transforming ecological responses from static constraints into optimization objectives that can be dynamically adjusted with management strategies. This approach enhances the ability to characterize the relationship between agricultural water use and ecological feedback. Although simplifications in the coupled hydrological model are inevitable, it still provides a more structured cognitive perspective for analyzing the trade-offs within the WEA system.

By simultaneously optimizing economic, ecological, and environmental objectives and presenting the feasible solution set via the Pareto frontier, this study systematically reveals the competitive and synergistic relationships among the objectives. This explicit expression of trade-offs helps decision-makers move beyond simple "either-or" thinking and conduct trade-off decisions within a more systematic cognitive framework.

It should be noted that this research framework is based on necessary simplifications of the complex WEA system, and the reliability of the optimization results highly depends on the accuracy of input data and parameters. If this method is to be extended to other basins, its applicability does not depend on the simple transplantation of models or data, but on the ability to implement spatially differentiated management according to local conditions and to make targeted adjustments by integrating the local data foundation with management objectives. For example, in regions lacking hydrogeological data, a more generalized hydrological model could be used to represent the water cycle processes. When the accuracy of crop spatial distribution data is limited, statistical data can be used to impose total area constraints at the regional scale. Furthermore, attention should be paid to uncertainty factors that significantly influence the optimization results (such as key hydrogeological parameters and agricultural management parameters), and their impact on decision-making outputs should be quantified through sensitivity analysis to provide necessary risk warnings for practical applications.

The case study of the Tarim River mainstream demonstrates that coupling key WEA processes, integrating multi-source data, and quantifying multi-objective trade-offs can provide valuable decision support for the integrated management of inland

river basins in arid regions. The research framework presented in this study may provide useful insights for other basins facing similar water resource challenges, although it should be further adapted and validated according to local conditions.”

Minor Comments

1. Line 23 Please unify the units used in the manuscript, such as hm, km, etc., throughout the text.

Response: We have standardized and unified the units throughout the manuscript. The area unit has been consistently expressed as hm², and the volume unit has been consistently expressed as 10⁴ m³.

2. Line 51 References should be added here. Also, references are lacked in some parts of the remain Introduction.

Response: We have added the requested references at Line 51 and throughout the relevant parts of the Introduction.

“The mainstream reach of the Tarim River Basin represents a representative arid inland river system in China (Wang et al., 2020). Agricultural production in this region is highly dependent on hydraulic infrastructure and is characterized by intensive irrigated agriculture (Hartmann et al., 2016). Long-term and large-scale abstraction of groundwater and diversion of surface water for irrigation have supported regional agricultural development and food security. However, these practices have also resulted in pronounced ecosystem degradation, manifested by declining groundwater levels, intensified desertification, and the shrinkage of terminal lakes (Lu et al., 2026; Zhang et al., 2013; Pang et al., 2010). Consequently, the need to balance agricultural water use with ecosystem stability has become a critical concern for the oversight of water resources in the Tarim River Basin.”

References

Hartmann, H., Snow, J. A., Su, B., and Jiang, T.: Seasonal predictions of precipitation in the Aksu-Tarim River basin for improved water resources management, *Glob. Planet. Change*, 147, 86-96, <https://doi.org/10.1016/j.gloplacha.2016.10.018>, 2016.

Lu, C., Feng, Q., Gao, X., Liu, W., and Ning, T.: Human-water adaptation in drylands:

Reconciling water use and ecological security in arid inland river basins of China, *J. Clean. Prod.*, 542, 147561, <https://doi.org/10.1016/j.jclepro.2026.147561>, 2026.

Pang, Z., Huang, T., and Chen, Y.: Diminished groundwater recharge and circulation relative to degrading riparian vegetation in the middle Tarim River, Xinjiang Uygur, Western China, *Hydrol. Process.*, 24, 147-159, <https://doi.org/10.1002/hyp.7438>, 2010.

Wang, W., Chen, Y., and Wang, W.: Groundwater recharge in the oasis-desert areas of northern Tarim Basin, Northwest China, *Hydrol. Res.*, 51, 1506-1520, <https://doi.org/10.2166/nh.2020.071>, 2020.

Zhang, X., Chen, Y., Li, W., Yu, Y., and Sun, Z.: Restoration of the lower reaches of the Tarim River in China, *Reg. Environ. Change*, 13, 1021-1029, <https://doi.org/10.1007/s10113-013-0403-0>, 2013.

3. Line 83-87 This paragraph is unnecessary.

Response: According to your suggestion, we have removed the content in Lines 83-87 to improve the conciseness and logical coherence of the manuscript.

4. Line 158 This is the first time GSFLOW appears, and it is recommended to provide a brief introduction. However, since this section is actually about the Data, please briefly introduce GSFLOW in the appropriate place.

Response: Thank you for this suggestion. We have added a brief introduction to the GSFLOW model in Section 3.1.1 of the Methods section.

“GSFLOW is a physically based distributed coupled hydrological modeling system that integrates the PRMS (Precipitation-Runoff Modeling System) surface hydrological process module with the MODFLOW groundwater flow module to simulate surface water-groundwater interactions at the watershed scale (Markstrom et al., 2008). The model is capable of simulating key hydrological processes such as precipitation, evapotranspiration, infiltration, surface runoff, groundwater recharge, and stream-aquifer exchange.”

5. Line 261 Please unify the use of these symbols.

Response: We have comprehensively checked and unified the formulas and symbols in Section 3.2 and throughout the manuscript to ensure consistency in variable definitions and symbol usage.

(1) Groundwater depth is expressed as D , and groundwater level is expressed as H ;

(2) The subscript for groundwater grid cells is uniformly expressed as g , thus $H_{g,T}$ and $H_{g,1}$ replace the previous H_{iT} and H_{i1} ; the symbol i is used only to represent agricultural zones;

(3) A new subscript j is introduced to represent crop types ($j = 1, \dots, M$, where $M = 6$, representing maize, cotton, vegetables, melons, fruit trees, and oil crops);

(4) Agricultural economic benefit (Equation 10): the double-subscript variables A_{ij} , Y_{ij} , and I_{ij} are introduced to replace the previous single-subscript variables, indicating that these variables are determined by both agricultural zone and crop type;

(5) Total nitrogen load (Equation 13): N_{ij} replaces the previous N_i , indicating that this variable is determined by both agricultural zone and crop type;

(6) The water surface area of Taitema Lake is consistently represented as L_A in both the constraints and the objective functions.

6. Line 503 The order of the subfigures in the figure captions does not match their actual order.

Response: Thank you for pointing out this issue in the figure. We have checked and redrawn Figure 9, ensuring that the subfigure labels from (a) to (o) correspond sequentially to the 15 representative solutions (S1-S15) discussed in the text.