Response to Comments of Referee #1

Major comments/questions

1. The model is formulated as a normative tool assuming perfect hydrologic foresight and a centralized, omniscient basin authority. While this is a standard and valuable approach for identifying ideal solutions, the manuscript should more critically discuss the implications of this assumption. Please expand the discussion (e.g., in Section 5.2) to explicitly address the gap between these normative results and the outcomes achievable under real-world conditions characterized by decentralized decision-making, political economy constraints, and imperfect information. Furthermore, the conclusion's claim of the model being a "replicable method" requires support. Please discuss the preconditions for transferability (e.g., data requirements, governance structure) and distinguish between generic model components (e.g., PMP, node-link architecture) and those that are context-specific.

Reply: We appreciate this insightful comment. It is important to clarify, however, that our framework is not a normative optimization tool. Rather, it represents largely a positive model with its irrigation component built upon the Positive Mathematical Programming (PMP) approach (Lines 276–289), which is designed to replicate and reflect the behavioral patterns of major water users, irrigation water use (> around 80% total water use), under observed conditions in the base year (Lines 101-105).

We acknowledge that the optimized results do not completely consistent with the real-world conditions:

1. First of all, the model as currently formulated is an optimization model, whose primary objective is to maximize net economic benefits (as specified in our objective function); consequently, its solutions will inevitably differ from real-world outcomes, as actual water allocation is driven by multiple goals and influenced by various constraints.
2. Regarding decentralized decision-making, water governance in the YRB adopts a hierarchical model, with highly centralized decision-making mechanisms. The Yellow River Conservancy Commission (YRCC) is the river basin authority with strong political and administrative mandates to coordinate and command flood control, water allocation, reservoir operation, and ecological flow releases across all provinces. Therefore, the model’s centralized decision-making assumption is consistent with the actual governance reality of the YRB, rather than a theoretical simplification.
3. Concerning political economy constraints, we acknowledge that this study does not explicitly include the full range of basin-wide or provincial political or economic regulations. Nevertheless, the model incorporates key policy-based water allocation constraints, most notably the *1987 Water Allocation Scheme* (Lines 329-336), which defines provincial water rights and effectively reflects the administrative limits imposed by the basin’s institutional framework. A more detailed policy analysis of YRB governance has been developed after this study and has been submitted to

another journal.

4. For imperfect information, this is discussed in both Section 3.2 (Model data and parameterization) and Section 5.2 (Limitations). We have emphasized these limitations and their potential implications for real-world applicability in the revised text in Section 5.2.

We recognize that the use of the term "replicable method" may have caused some misunderstanding. Our intention was that "replicable method" should refer to the transferability of the modeling concept and methodological approach, rather than a one-to-one replication of model configurations or even parameters for other basins. We will revise the manuscript accordingly, using "transferable framework" to avoid ambiguity. The model's core ideas, such as the node-link architecture, PMP-based calibration, integration of water supply and demand, and holistic hydrological–economic formulation, can be adapted and applied to other basins, while the specific implementation (e.g. conditions and functions of water infrastructure system, demand characteristics, water allocation policies, reservoir operational rules, etc.) must be tailored to the research questions, hydrological and socioeconomic settings, and data context of each basin.

2. The introduction and discussion could more sharply articulate the specific methodological advancements of this model compared to existing basin-scale or multi-basin hydroeconomic optimization frameworks. What are its unique features or integrative capabilities that provide new insights not possible with previous models? The manuscript should be refocused to highlight these novel, quantitative discoveries. Several central findings (e.g., agriculture's dominant water use, importance of reservoir coordination) are well-established qualitatively in the YRB literature. The paper's contribution would be significantly enhanced by shortening the lengthy study area description and expanding the analysis on surprising, nuanced, or quantitatively new results generated by the model.

Reply: Thanks for your comments regarding the novelty and uniqueness of our research. We have condensed the review of existing work in Section 1 and Section 3.1, and expanded the quantitative analysis to better highlight the distinctive features.

Specifically, the innovative aspects of our study are as follows:

(1) We developed a basin-scale hydroeconomic optimization model for the entire YRB that explicitly represents the interactions among all spatially distributed major water supply and demand sectors. The model achieves a fully integrated optimization of surface water, groundwater, and multi-reservoir coordination across the basin, linking water availability, infrastructure operation, and sectoral economic activities within a unified decision framework. This holistic design allows quantitative evaluation of trade-offs that were previously examined only qualitatively. To our knowledge, a basin-wide hydro-economic optimization model with this level of detail does not exist for the YRB, prior to this paper.

(2) Positive mathematical programming (PMP) calibration is embedded into the model, enabling the representation of realistic responses of land use and agricultural economic behaviors rather than purely normative efficiency assumptions.
(3) The model provides explicit estimates of benefits and marginal values by location, node (sector), and hydrological year type. These quantitative indicators reveal new patterns, including the spatial gradient of water scarcity along the basin, the varying degrees of scarcity across sectors, and the implicit economic value of water in non-revenue-generating sectors, thus offering valuable policy insights.

3. The finding that ecological water use carries a negative shadow price is a critical issue that arises from an incomplete accounting system which ignores the value of ecosystem services. Preferably, the authors should attempt to monetize and incorporate a subset of key ecosystem services (e.g., water purification, tourism, habitat provision) into the objective function, even via a simplified sensitivity analysis scenario. This would demonstrate how internalizing these non-market values alters the optimal allocation and provides a more holistic view of economic benefit.

Reply: We appreciate your valuable comment and suggestion. While we fully agree that monetizing key ecosystem services would provide a more comprehensive representation of ecological benefits, this recommendation unfortunately goes beyond the current scope of our research. In the YRB, ecological replenishment requirements are mandated by qualitative policy-oriented documents (The State Council of the People's Republic of China, 2021), and their implementation is carried out by the basin authority or local governments. Despite these qualitative regulatory mandates, unfortunately, there is no quantitative or monetized dataset available, either in existing studies or public databases to support the explicit valuation of ecological benefits arising from water allocation.

Introducing such estimates without robust empirical evidence would inevitably introduce biases and uncertainties into the optimization results and could compromise the internal consistency of the model. For this reason, our current formulation represents ecological water use through explicit flow constraints that guarantee a minimum ecological water supply for designated zones, mainly to prevent drying-up and the associated loss of biodiversity and ecosystem integrity. The absolute value of shadows prices for ecological water use can still indirectly reflect the competing relationship with other economic sectors and its impact on the objective function (Section 4.4).

Reference:
[1] The State Council of the People's Republic of China: Outline of the Yellow River Basin's Ecological Protection and High-quality Development Plan, 2021.

4. The model treats groundwater as a simple storage node, ignoring dynamic feedbacks such as declining water tables increasing pumping costs and altering river-aquifer

interactions. Does the model's optimal solution systematically encourage groundwater overdraft by not internalizing the increasing marginal cost of extraction?

Reply: We appreciate this insightful comment and we acknowledge that the current version of the model simplifies groundwater representation. Specifically, the groundwater component is modeled at the node scale, focusing primarily on the exchange and allocation of flows between nodes rather than detailed aquifer dynamic feedbacks. We have expanded the discussion in Section 5.2 for the simplification of groundwater module design.

While our research indicates that the pumping cost increases as the groundwater table drops. The pumping cost (Section 2.1 Eq. 3) is calculated as a function of average lifting height and withdrawal volume, reflecting the energy required to lift water from the aquifer. Therefore, as the groundwater table declines, the corresponding pumping cost increases, which introduces an implicit economic disincentive against over-extraction.

Moreover, the model explicitly constrains groundwater extraction by assigning a minimum allowable water-table level to each groundwater node. This prevents withdrawals from exceeding the real-world safe limits. According to the *Yellow River Water Resources Bulletins* (see yrcc.gov.cn, in Chinese), the average annual groundwater extraction in the basin is approximately 10 to 11.6 billion m^3, which aligns with the aggregate limits represented in the model.

5. The sediment challenge, central to the YRB, is reduced to a constraint. The massive opportunity cost of water used for sediment flushing is excluded from the economic objective function. Please discuss how this omission might bias the optimal allocation between sectors.

Reply: Thank you for your insightful comment. The term "constraint" in our model can relate to two different components, and we respond to each possibility below.

(1) If you refer to the "21 billion m^3 (water) for sediment flushing" to the sea (Line 322) specified in the *1987 Water Allocation Scheme*:
This quantity represents a policy-oriented static target, rather than a practical operational requirement. In both real-world management and in our model, this target is not enforced as a fixed constraint. Instead, we implement a minimum flow requirement to the Bohai Sea of 50 m^3/s, which is a binding rule to ensure the continuity of river flow and prevent flow interruption, and aligns with the actual operational practice

(2) If you refer to the reservoir constraints for sediment flushing in Table S1:
In our model, sediment control is represented through reservoir operation rules, particularly for the key downstream reservoirs such as Sanmenxia Reservoir and Xiaolangdi Reservoir. Specifically, we incorporate sediment flushing constraints

that regulate reservoir releases and elevations during designated sediment-flushing months. These rules are embedded in the reservoir operation module and are consistent with the sediment management practices implemented by the YRCC.

It is important to clarify that, in our model formulation, sediment-flushing releases are treated as part of the normal reservoir outflow rather than as a separate or consumptive water use. After being released (e.g., from Sanmenxia Reservoir and Xiaolangdi Reservoir), this water continues to flow downstream through the main river channel and becomes available to meet subsequent downstream demands, including irrigation, ecological flows, and municipal/industrial supply. Accordingly, sediment-flushing releases remain fully accounted for within the basin's mass-balance constraints and the optimization framework. In other words, the model does not treat sediment flushing as a terminal or isolated use; the released water continues to contribute to downstream allocation decisions.

6. The description of the "baseline calibration" is vague. The manuscript would be significantly strengthened by providing quantitative goodness-of-fit metrics (e.g., R^2, Nash-Sutcliffe Efficiency, Percent Bias) for key variables like streamflow at key gauges, reservoir storage, and agricultural water use against observed data. Additionally, the choice to fix socioeconomic conditions at the 2020 level while using 1996-2015 hydrology should be explicitly justified, and its potential impact on the results discussed.

Reply: Thanks for your constructive comments. We have added a table of goodness-of-fit metrics in the supplementary material to evaluate the model's performance for major hydrological gauge stations, reservoirs' end-of-year storage values, and agricultural water use against observed data. These evaluations are based on Percent Bias (PBIAS) and Normalized Root Mean Square Error (NRMSE). The results show that the deviations between modeled and observed values are within an acceptable range (PBIAS ±10% and NRMSE between 10% to 30%), demonstrating that the model adequately reproduces the basin's hydrological and allocation patterns.

Regarding the use of the 1996–2015 hydrological data series, our hydroeconomic optimization model adopts a planning-model framework, consistent with widely used basin-scale models such as the California Value Integrated Network (CALVIN) model (Draper et al., 2003; Harou et al., 2009), as well as the official planning practices of the basin authority YRCC (YRCC, 2015), in which 2020 and 2030 were selected for water demand and supply planning. These approaches typically fix a recent representative planning year or period as the baseline for evaluation. The period of 1996–2015 was selected because it represents the most recent and reliable continuous hydrological dataset available for the YRB.

Using a multi-year series instead of a single-year hydrology allows us to capture the basin's large interannual variability, thereby providing a more robust representation of hydrologic conditions and avoiding the bias and uncertainty associated with using a single hydrologic year. Moreover, the Yellow River includes multi-year regulating reservoirs, such as the Longyangxia Reservoir. Using continuous multi-year data enables the model to realistically run cross-year regulation and storage behavior, which would not be possible under a single-year hydrologic assumption.

Reference:
[1] Draper, A. J., Jenkins, M. W., Kirby, K. W., Lund, J. R., and Howitt, R. E.: Economic-Engineering Optimization for California Water Management, J Water Resour Plan Manag, 129, 155–164, https://doi.org/10.1061/(asce)0733-9496(2003)129:3(155), 2003.
[2] Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., and Howitt, R. E.: Hydro-economic models: Concepts, design, applications, and future prospects, J Hydrol (Amst), 375, 627–643, https://doi.org/10.1016/j.jhydrol.2009.06.037, 2009.
[3] YRCC: Executive Summary of the Yellow River Basin Comprehensive Planning 2012-2030 (in Chinese), http://yrcc.gov.cn/zwzc/ghjh/202312/t20231220_365017.html, 2015.

7. The economic conclusions are highly sensitive to exogenous parameters (crop prices, electricity tariffs, demand elasticities). The absence of a comprehensive sensitivity analysis on these key parameters leaves the robustness and reliability of the optimal solution unclear. A demonstration of how the main conclusions hold under different parameter values is essential.

Reply: We thank the reviewer for pointing out the absence of a comprehensive sensitivity analysis in the manuscript. We provide below explanations for the key parameters you mentioned:

(1) Crop price: Due to high output of crop production and government support for price stabilization policies in the YRB, prices remain relatively stable (2020 Price Division of National Development and Reform Commission of the People's Republic of China, in Chinese). According to a study done for the Hetao Irrigation District (HID) within the YRB (Cao et al., 2023), area responses of staple crops are only marginally affected by price fluctuations. Meanwhile, the cash crops considered in our model account for a relatively small area share despite their considerable market volatility, thus their overall impact remains small on land use, water allocation and net benefit. We adopt real-world data for crop prices and consider the crop price parameters as relatively stable for our optimization model.
(2) Electricity tariff: Electricity tariffs are predominantly set by government regulation rather than by market forces (please see government documents by State Council General Office, https://www.gov.cn/zhengce/202504/content_7016955.htm, in Chinese). Accordingly, we use the actual values set by the government and treat this parameter as stable.
(3) Demand elasticities: Estimating water demand elasticities for urban sectors (industrial and municipal) is methodologically challenging and constrained by

limited data. Developing robust elasticity estimates requires extensive sectoral survey data and econometric modeling, which is beyond the scope of the present study. In our model, we therefore rely on elasticity values drawn from the literature, treating them as fixed and reliable inputs.

Reference:

[1] Cao, Z., Zhu, T., and Cai, X.: Hydro-agro-economic optimization for irrigated farming in an arid region: The Hetao Irrigation District, Inner Mongolia, Agric Water Manag, 277, https://doi.org/10.1016/j.agwat.2022.108095, 2023.

8. Please provide a justification for why a monthly time-step is sufficient to capture critical processes such as flood peaks, short-term crop drought stress, or reservoir flood control rule curves. Furthermore, a discussion on the potential for extending the framework to stochastic optimization or scenario-based analysis for future climate and socioeconomic pathways would be a valuable addition to the "Limitations and Future Developments" section.

Reply: We thank the reviewer for this thoughtful comment regarding the model's temporal resolution. The choice of a monthly time step was made to balance the need for hydrological realism with computational feasibility for a basin-scale, multi-sector optimization covering multiple decades. This temporal resolution is consistent with the management and reporting frequency adopted by the provincial governments to the YRCC.

While we acknowledge that a monthly time step cannot fully resolve some abrupt changes, some short-term processes can still be partially reflected:

(1) Flood peaks: Although daily or sub-monthly flood routing is beyond what the temporal resolution of our model can capture, the aggregated variability of monthly inflows can still reflect the occurrence and hydrological impact of high-flow events. These variations influence reservoir releases and downstream water availability in the optimized monthly results.

(2) Short-term crop drought stress: Crop-level water stress is represented at sub-seasonal level in the model, which is determined by monthly water allocation decisions within each irrigated district.

(3) Reservoir flood control: The model considers reservoir operations over the entire flood seasons (summer-autumn flood season from July to Oct., and ice-flood season from Nov. to Feb.) by sticking to flood control storage rules and release rules, rather than conducting short-term flood routing daily or at an even smaller time interval. Therefore, the monthly time step is appropriate for representing storage regulation during flood seasons. Thus, the resulting storage–release relationships from the optimization outcomes also reflect the key operational rules and flood control strategies adopted by major reservoirs in the basin.

We agree that extending the current deterministic framework to incorporate stochastic optimization or scenario-based analysis under future climate and socioeconomic uncertainties is a highly valuable direction for future research. We have added this point explicitly in Section 5.2, noting that the existing model structure is well suited for such extensions.

Minor comments/questions

1. The abstract contains many summary statements but lacks powerful, concrete data. Please include 1-2 of the most striking quantitative results to enhance its impact.

Reply: Thanks for your valuable suggestion. We have added one of the study's most distinctive quantitative results, highlighting the spatial coupling between hydrological scarcity and economic valuation across the YRB. The revised sentence in the abstract reads as follows:

"Results reveal that water availability decreases by approximately 75% from upstream to downstream, with the corresponding marginal value rising from 0 to 9.14 yuan/m^3 in a severe dry year..."

2. There is inconsistent use of terms (e.g., "Hydropower" in figures vs. "Hydroelectricity" in text). A thorough check to unify terminology is required.

Reply: Thanks for your observation. We carefully reviewed the manuscript and standardized all terms to "Hydropower" throughout the text and figures. The modified parts are at Line 159, Line 161 and in Table S1.

3. Ensure all variables and parameters are explicitly defined upon their first use in the main text.

Reply: We appreciate your suggestion. We have checked and modified Line 175-176, Line 209-210, and Line 215, confirming that all variables and parameters are now explicitly defined at first mention in the main text and the corresponding supplementary materials.

4. Some figures, particularly Fig. 10 and Fig. 11, are data-dense and challenging to interpret. Improving clarity with better annotations, labels, or a simplified presentation would enhance reader comprehension.

Reply: We sincerely appreciate your concern regarding figure clarity. We have double-checked the labeling and legend formatting and have decided to maintain the current level of detail for most figures. For Fig. 10, we have enlarged font size to improve readability; and for Fig.11, we have moved the position of the x-axis label "upstream→downstream" to the top, and added a description of the labels in the figure's title.

5. The supplementary material is extensive and helpful. However, please ensure that all tables and figures in the supplement are explicitly referenced at the relevant points in the main manuscript.

Reply: We appreciate your positive comment on the supplementary materials. In response to Major Comment 6, we have added a new table in the supplementary material. Meanwhile, the original Figure S3 and Table S4 were removed. Accordingly, some adjustments have been made in the table numbering and coding. We have also ensured that all tables and figures in the supplementary material are now referenced and consistent with those in the main manuscript.

6. The "Limitations" section should be revised to explicitly acknowledge the points raised in this review regarding governance assumptions, dynamic hydrological feedbacks, and valuation shortcomings.

Reply: We appreciate the reviewer’s valuable suggestion. Following the major comments provided earlier, we have revised and expanded Section 5.2 accordingly to present the assumptions, constraints, and potential future extensions more clearly.