Reply to Referee #1

Dear reviewer,

First of all, we would like to thank you for the time you have spent reviewing our manuscript. We strongly appreciate the comments for further improvements and valuable feedback made. We have carefully addressed the reviewer's comments and suggestions, and revisions have been made in the revised manuscript. Below are our point-by-point responses to the comments in blue text.

Author and Co-Authors

COMMENTS FROM REVIEWER#1

The main objective of this paper is to provide a new perspective to analyze eco-hydrological systems based on network approaches. The integrated framework characterized the joint evolution and causal interactions in the complex system at the levels of "phenomena" and "mechanisms", respectively. In particular, I think this study made good attempts to clarify causality between variables of different types (runoff, soil water storage, groundwater storage, normalized difference vegetation index, gross primary productivity, water use efficiency, etc.) by constructing causal networks. The framework was then applied in the Yellow River Basin, China. The results are generally interesting and reasonable. This paper is overall well-structured and well-written.

Despite the proposed framework is promising, the manuscript requires improvements to better illustrate both the methodology and the results sections. In addition, some grammatic errors and figures should be revised. Below are the detailed comments for consideration.

Reply: Thank you for your positive evaluation of our manuscript and your suggestions. We have carefully reviewed and revised our manuscript according to your comments.

Comments in details

1. Methodology: The flow chart and a large amount of eco-hydrological variables appear abruptly.

Before introducing the flow chart and methods, I suggest adding a concept diagram depicting interactions between the hydrosphere and the biosphere. This diagram should illustrate the eco-hydrological processes in greater detail than Figure 2. Then the authors are suggested to explain why they have chosen these variables (R, TWSA, SMSA, GWSA, NDVI, etc.) for this study.

Reply: Thank you for pointing out this issue. The following conceptual figure depicts the eco-hydrological processes in a watershed.

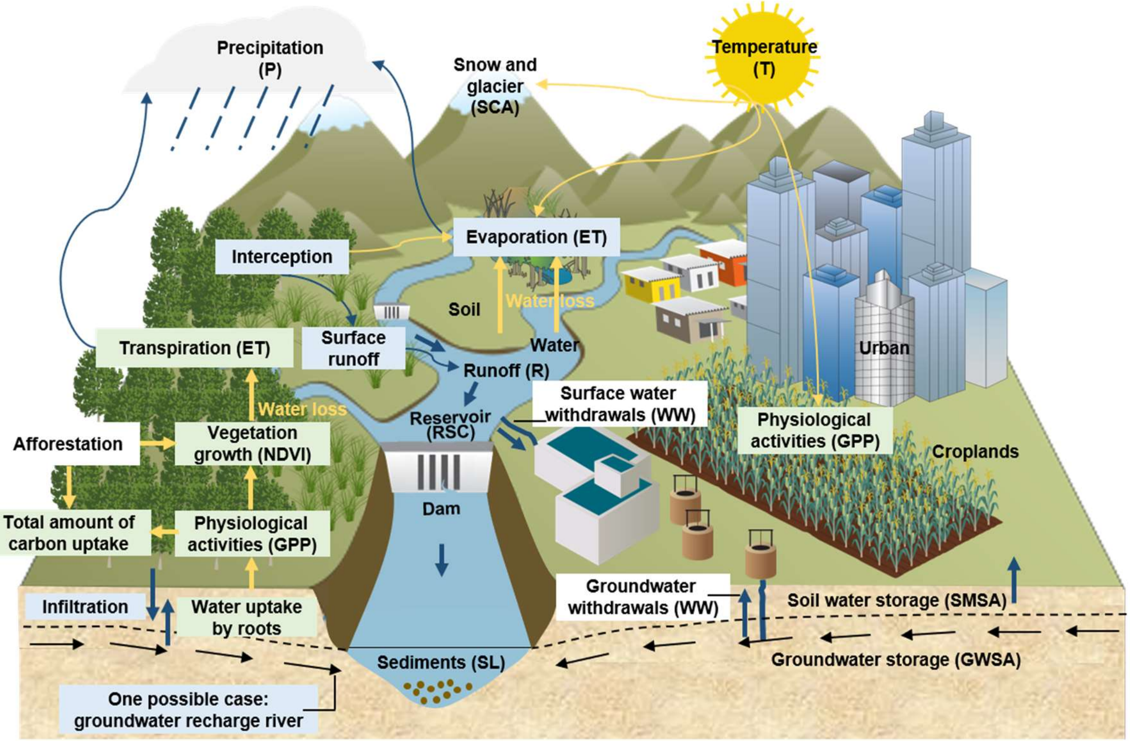


Figure 1. Conceptual illustration of the eco-hydrological processes in a watershed. The blue rectangles are related to hydrological processes, the green rectangles are associated with ecological processes and the white rectangles indicate human activities.

Due to the complexity of the processes, we selected some typical variables to characterize the eco-hydrological system, as well as the main influential factors to the system. Our study focuses on coupled ecology-hydrology feedbacks at the land surface so that climate forcings are treated as external factors. The eco-hydrological variables are as follows:

Hydrological variables: Regional runoff (R), soil water storage (SMSA), and groundwater storage (GWSA) are chosen as the main hydrological variables. Besides, regional sediment load (SL) is selected since the Yellow River is known for high sediment loads and efforts have been made to address this problem. Additionally, the Yellow River originates in the Tibetan Plateau, which has snow and glaciers, so we consider the snow cover (SCA). Some more detailed processes, such as infiltration, are not included due to the challenges of accurately quantifying them with the available data sets.

Ecological variables: Vegetation coverage and physiological characteristics are mainly taken into account. Three variables, namely, normalized difference vegetation index (NDVI), gross primary productivity (GPP), and ecosystem water use efficiency (WUE) are used to represent vegetation growing condition, carbon uptake condition, and the trade-off between carbon gain and water loss (evapotranspiration, ET) of terrestrial ecosystems, respectively.

Influencing factors: The two main climatic factors, i.e. temperature (T) and precipitation (P), as well as the influence of reservoirs (RSC) and water withdrawals (WW), are considered. Data on sunshine duration, wind speed and relative humidity are also available from meteorological stations. However, monthly sunshine duration and monthly relative humidity in YRB are found to be highly correlated with monthly precipitation, and these two variables are not considered due to redundancy. In addition, the influence of wind speed on eco-hydrological processes is insignificant compared to T and P, so this factor is not included.

As suggested, we will add the conceptual illustration and some justification for using these variables in the revised manuscript (Section 2).

2. Line 152: There are many causal inference methods other than PCMCI, such as Convergent Cross Mapping (CCM) and Granger Causality (GC). Can you briefly explain why PCMCI was used in this study?

Reply: Thank you for your comments. We fully agree that several methods have been developed over the last few decades for inferring causal relationships from observational data.

Granger causality (GC; Granger, 1969) assumes that the cause provides useful information for predicting the effect at future time steps, and any variable in the system can be represented linearly by lagged values of system variables and an error term. This means that two variables occurring at the same time cannot be causally related. Our study is conducted on a monthly time scale (limited by the data obtained) at which many eco-hydrological processes occur below the data's time resolution, and many contemporaneous relationships will be produced. Additionally, multivariate extensions of GC could fail if too many variables are considered (Runge et al., 2019).

Convergent cross-mapping (CCM) infers causality between two variables in nonlinear dynamical systems (Sugihara et al., 2012). If variable *X* can be predicted using the reconstructed system based on the time-delay embedding of variable *Y*, then we know that *X* had a causal effect on *Y*. In general, CCM is restricted to strictly deterministic systems and is therefore less suitable for time series that are stochastic in nature. Moreover, a high false-positive rate was reported when using the CCM, explained by CCM's inability to deal with confounding and synchrony (Ombadi et al., 2020; Delforge et al., 2022). CCM does not have the significance assessment for causality as well.

In this study, PCMCI is employed for the following reasons: (1) PCMCI addresses the challenges regarding autocorrelated, high-dimensional time series data by first using a condition-selection step (PC) and then applying a momentary conditional independence (MCI) test. (2) In contrast to GC, PCMCI is more efficient, deals with contemporaneous effects, and provides significant causal links with different time delays. (3) Compared to CCM, PCMCI is easier to use (nonparametric tests) and has a significance assessment for causal links (Runge et al., 2019).

As suggested, the explanation of why PCMCI was used in this study will be added in the revised manuscript in brief.

References:

Granger, C. W. J.: Investigating causal relations by econometric models and cross-spectral methods, Econometrica 37, 424-438, 1969.

Sugihara, G. et al.: Detecting causality in complex ecosystems, Science, 338, 496-500, 2012.

Ombadi, M., et al.: Evaluation of methods for causal discovery in hydrometeorological systems, Water Resources Research, 56, e2020WR027251, 2020.

Delforge, D., et al.: Detecting hydrological connectivity using causal inference from time series: synthetic and real karstic case studies, Hydrol. Earth Syst. Sci., 26, 2181-2199, 2022.

Runge, J., Bathiany, S., Bollt, E. et al.: Inferring causation from time series in Earth system sciences, Nat. Commun., 10, 2553, 2019.

3. Line 154: Provide a full name of PC as the term is first appeared.

Reply: Thank you for your careful examination. We have corrected in the revised manuscript.

4. Equation (6): The symbol of ⊥ is not clarified.

Reply: Here "⊥" denotes independence. We have added more clarification on Equation (6) in the revised manuscript.

5. Line 190: I think a citation is required for the additive model.

Reply: Two references of Ombadi et al. (2020) and Poppe et al. (2023) have been added, in which the anomalies of observations are calculated by subtracting the seasonality and removing the linear trend in a similar way.

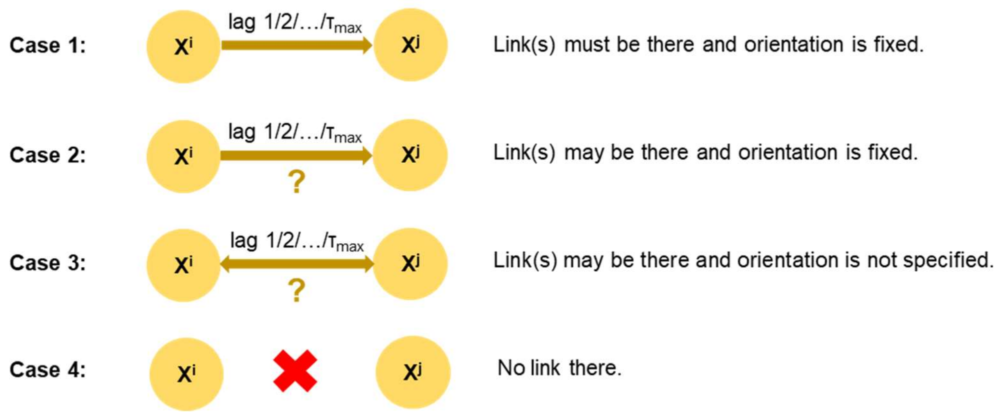
References:

Ombadi, M., et al.: Evaluation of methods for causal discovery in hydrometeorological systems, Water Resources Research, 56, e2020WR027251, 2020.

Poppe Terán, C., Naz, B.S., Graf, A. et al.: Rising water-use efficiency in European grasslands is driven by increased primary production, Commun. Earth Environ., 4, 95, 2023.

6. Section 2.3.3: This section is interesting, but how such possible links (physical constraints) incorporated to the causality algorithm (PCMCI) is not clear enough. More explanation is needed.

Reply: Thank you for your comment. Sometimes, researchers have prior knowledge about the presence or absence of links and their orientations. There are three types of link assumptions, they are: (1) the assumption that the link from variable X^i to X^j at any lag must exist, and its orientation is fixed (Case 1); (2) the assumption that the link from variable X^i to X^j at any lag may exist, and its orientation is fixed (Case 2); and (3) the assumption that the link from variable X^i to X^j at any lag may exist, but its orientation is not specified (the orientation is then given by the time order; Case 3). In our study, we mainly use the second type of assumption to specify the direction of contemporaneous links. Some interactions are potentially bidirectional, in which case the third type of assumption is used.



Based on the research objectives, some physically "impossible" causal links are also assumed to make the results concise and are not tested in the causality analysis. For example, we assume that WUE is influenced by changes in ET or GPP, so the links directly linking factors such as T and P to WUE are considered inappropriate (Case 4). Precipitation does not appear to be able to directly influence groundwater, so we have removed this for the PCMCI test. Such expert knowledge is incorporated by adding the link_assumptions function to the PCMCI algorithm of the Python package tigramite (https://github.com/jakobrunge/tigramite).

As suggested, more explanation on this will be added in the revised manuscript.

7. Lines 230-236: The Yellow River Basin is divided into several subregions, but the general conditions of these regions are not fully introduced. I suggest that more information on this should be presented, in order to help explain the eco-hydrological mechanisms in the following sections and to help the readers easily relate different subregions to their corresponding results.

Reply: Thank you for making us notice. In Section 3.1, we have reorganized the sentences and focus more on introducing the general conditions of the subregions. The detailed modifications in the revised manuscript are as follows:

The upper reaches include Regions I-IV, covering part of the Qinghai-Tibet Plateau and the driest parts of the Loess Plateau. The source region (Region I), located above the Guide (GD) station, has a cold and vulnerable eco-environment where the climate is inland alpine semi-humid, generating 35% of the total annual runoff for the entire basin (Zhan et al., 2024). From west to east, altitude gradually decreases, temperature increases and the climate becomes drier. Region II serves as a transition zone between the source (Region I) and the Loess Plateau (Regions III and IV). Regions III and IV are the driest parts of the Yellow River Basin, characterized by low precipitation, high evapotranspiration and sparse vegetation coverage. The dominant land use type in the upper reaches is grassland (Cao et al., 2022). It should be noted that the Region IV is an endorheic area with no runoff.

The middle reaches are Regions V-VII between Toudaoguai (TDG) and Huayuankou (HYK) stations and the lower reaches are Region VIII downstream of HYK. These areas have a warm-temperate continental monsoon climate (Zhang et al., 2022), with warmer and wetter climatic conditions and better vegetation coverage from Region V to Region VIII. The main land use type types in the middle and lower reaches are cropland and forest. Compared with the upper reaches, these regions have experienced more intensive human activities, including the return of cropland to forests and excessive water withdrawals for large populations, agricultural irrigation and industrial production (Zhou et al, 2024; Xie et al., 2019).

References:

Cao, Y.P., Xie, Z.Y., Woodgate, W., et al.: Ecohydrological decoupling of water storage and vegetation attributed to China's large-scale ecological restoration programs, J. Hydrol., 615, 128651, https://doi.org/10.1016/j.jhydrol.2022.128651, 2022.

Xie, J.K., Xu, Y.P., Wang, Y.T., et al.: Influences of climatic variability and human activities on terrestrial water storage variations across the Yellow River basin in the recent decade, J. Hydrol., 579, 124218, https://doi.org/10.1016/j.jhydrol.2019.124218, 2019.

Zhan, H., Yu, D.X., Wang. L., et al.: Stronger influences of grassland growth than grassland area on hydrological processes in the source region of the Yellow River, J. Hydrol., 642, 131886, 2024.

Zhou, J.L., Liu, Q., Liang, L.Q. et al.: Water constraints enhanced by revegetation while alleviated by increased precipitation on China's water-dominated Loess Plateau, J. Hydrol., 640, 131731, 2024.

Zhang, K.Z., Dong, Z.C., Guo, L., et al.: Allocation of flood drainage rights in the middle and lower reaches of the Yellow River based on deep learning and flood resilience, J. Hydrol., 615, 128560, 2022.

8. Line 242: I would like to change "which is divided" into "with the basin divided".

Reply: Thanks. We have revised the text as suggested.

9. Lines 266-268: The ways to calculate surface water storage and soil water storage are not clear. For example, what specific components from GLDAS are included in soil water storage/surface water

storage? Please add some details.

Reply: In our study, soil water storage (SMS) is calculated as the total of soil moisture content from four different soil layers (0-10 cm, 10-40 cm, 40-100 cm, and 100-200 cm) simulated by the Noah land surface model. Surface water storage (SWS) contains snow water equivalent and canopy water storage from Noah land surface model, and water stored in reservoirs. More details will be stated in the revised manuscript.

10. Line 268: Revise “soil moisture storage water storage”.

Reply: Thanks. We have revised the text as suggested.

11. Line 287: Change “withdrawals” to “withdrawal”.

Reply: Thanks. We have revised the text as suggested.

12. Figures 4 (a)-(h): Labels for horizontal coordinates are missing.

Reply: The horizontal axis represents the year from 2003-2019, and we have revised this figure.

13. Figure 5: I think it is better to present the S values (i.e., the synchronization between the two subsystems) in Figure 5b as well.

Reply: Thank you for your suggestion. The *S* values have been added in the revised manuscript.

14. Figure 6: This figure is very important, but some of the lines are not clear enough (especially the dash lines). In addition, the resolution of the figure should be improved.

Reply: Thank you for the comments. The width of the dash lines has been increased.

15. Line 336: Change “increase” to “increases”.

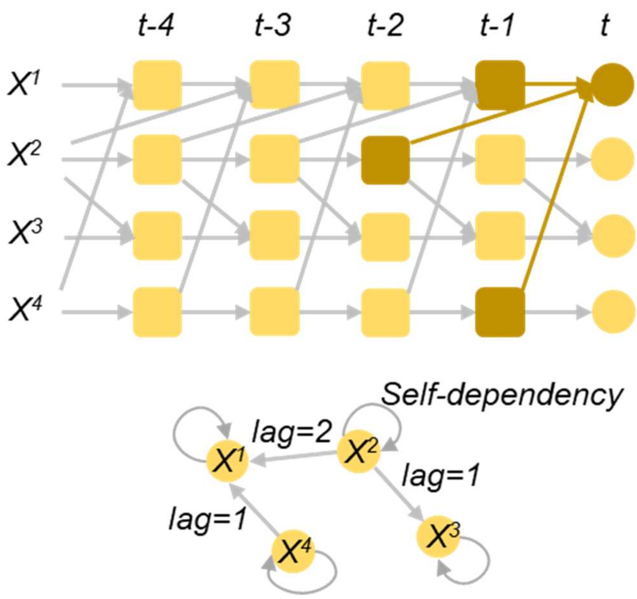
Reply: We have revised the text as suggested.

16. Line 407: Change “insignificant WUE decrease” to “an insignificant WUE decrease”. Change “significant WUE decrease” to “a significant WUE decrease”.

Reply: We have revised the text as suggested.

17. Line 435: I know that PCMCI can calculate autocorrelation of each variable when performing causality analysis. However, I do not see any results regarding autocorrelation. I suggest to add more details about this or just remove "autocorrelation" in this sentence.

Reply: Thank you for your comments. We did not clearly explain the flow of information between time-series variables in the methodology section, nor did we illustrate the autocorrelation. The following figure is a simple example of the causal process network, where variables may have self-dependency (i.e., autocorrelation) and cross-dependency (i.e., forcings from other variables) with different time lags (Goodwell et al., 2020). For the variable X^1 at time t (the brown circle), its variation is driven by X^1_{t-1}, X^2_{t-2}, and X^4_{t-1}. Therefore, we said that "the phenomenon of synchronous increases is controlled by a combination of common drivers, respective drivers, autocorrelation, and causality". Nevertheless, the autocorrelation results of eco-hydrological variables are not important as the study focuses on the interactions between these variables. In this case, we will add some results on this in the Supplementary Material.



References:

Goodwell, A.E., Jiang, P.S., Ruddell, B.L, et al.: Debates—Does Information Theory Provide a New Paradigm for Earth Science? Causality, Interaction, and Feedback, Water Resour. Res., 56, e2019WR024940, https://doi.org/10.1029/2019WR024940, 2020.

18. Line 534: Change “to understand” to “for understanding”.

Reply: Thanks! We have revised the text as suggested.