Peer Review File

Climate change and human activities amplify runoff variability risks in lower reaches of large rivers

Corresponding Author: Professor Chunhui Li

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Professor Li,

Your manuscript titled "Climate change and human interventions induce larger runoff variability risks in the lower reaches of major river basin" has now been seen by 2 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication in its current form, but would be interested in considering a revised version that fully addresses these concerns.

Specifically, we require that you:
-apply the Budyko framework strictly to long-term mean values (e.g., decadal averages) and revise the attribution logic to separately quantify climate- and human-induced runoff changes;
-justify the evapotranspiration estimation method used and validate it through Budyko plots showing how long-term P, PET, and Ea align with theoretical curves;
-incorporate a causal analysis approach (e.g., PCMCI+) to move beyond simple correlations and better isolate the drivers of runoff variability under climate and anthropogenic influences;
-streamline the periodization by limiting sub-divisions unless strongly justified, and enhance result clarity by visualizing catchment movement in Budyko space before and after the change points.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Rahim Barzegar, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-1941-2991

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Please see attached file.

Reviewer #2 (Remarks to the Author):

The contributions of climate change and human interferences to runoff variation and their spatiotemporal differences have been examined in multiple independent unit catchment areas; however, comprehensive investigation into the interaction relationships between upstream and downstream sub-catchment areas is lacking. Here, we propose a new three-tiered framework for attributing runoff variation to investigate the spatiotemporal patterns, driving factors, and interaction mechanisms between upstream and downstream under climate change and human activities over a 70-year period (1952-2021) in the Yellow River Basin. This topic is interesting and within the scope of Communications Earth and Environment.

In the Abstract, I would recommend providing more statistical results.

The Budyko has been widely used in attributing and detecting human/climate changes in hydrological cycle. The advancement of this paper should be discussed.

The streamflow data is difficult to collect in China. Could you provide more details about the open access way to access to these series?

It is widely reported that upstream and downstream usually have different evolution pattern. More discussion is necessary.

This study identified dominant factors of changes in runoff. However, some physical mechanisms are lacking.

I find the English should be improved.

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Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Professor Li,

Your manuscript titled "Climate change and human activities amplify runoff variability risks in lower reaches of large rivers" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

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** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Rahim Barzegar, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-1941-2991

Aliénor Lavergne, PhD
Senior Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I would like to commend the authors for their substantial and thoughtful revisions. The manuscript has significantly improved in clarity, methodological rigor, and scientific contribution. I particularly appreciate the revised attribution framework, the re-quantification based on multi-year averages, and the integration of the PCMCI+ causal discovery method. These additions strengthen the overall analytical approach and support the main conclusions more robustly.
The authors have addressed the concerns raised in the previous round in a clear and constructive manner. The writing is much clearer, and the structure of the paper flows better.

That said, I have a few minor comments for further refinement:

Both Figure 2 and Figure 3 are quite crowded and not easy for the reader to follow.
In Figure 2, please increase the font size, particularly for axis labels and annotations. Currently, the small text makes it difficult to read, even at full zoom.

In Figure 3, the same issue applies—at minimum, please increase the font size for the subtitles and the labels "Period 1", "Period 2", "Period 3", "Period 4", as well as "Period I" and "Period II", which are hard to read in the current format. If possible, you can consider simplifying the two figures.

Figure 8 – Inconsistent Color Mapping: Please double-check the colormap used to display MCI values in Figure 8. There appears to be an inconsistency in how the values are represented. In some cases, the color scale implies a range from -1 to 1, using diverging blue-red tones (suggesting both positive and negative correlations), while in other parts, the scale seems to reflect a range from 0 to 1, which is appropriate for MCI values that should be non-negative. This inconsistency can be misleading to readers interpreting the causal strengths. Please ensure that the color scale is consistent and correctly reflects the theoretical range of MCI values (typically [0, 1]), and update the legend and caption accordingly.

Sub-catchment Labels in Figures: In several figures (e.g., Figures 2, 4, 5, and 6), sub-catchments are labeled using two-letter abbreviations. While this may be meaningful to the authors, it can be confusing for readers unfamiliar with the basin. I recommend consistently labeling the sub-catchments using the standardized identifiers (S1 to S20), as introduced in Figure 1. This labeling system is intuitive, reflects the sub-catchments' order along the main river course, and would greatly enhance the readability and interpretability of the figures across the manuscript.

The referencing of figure 1 could be improved. Figure 1 is first mentioned at the end of the Introduction, but its relevance and placement are unclear. It would help to refer to it later in the “Data and data processing” when describing the study region or move its citation to better align with surrounding content. I would also suggest change the title of subsection to “Data sources and processing”

With the above minor revisions, particularly those aimed at improving figure readability, I believe this paper will make a valuable contribution to the field of hydroclimatic change and river basin management.

Reviewer #2 (Remarks to the Author):

I am happy to accept this manuscript.

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The manuscript explores the attribution of streamflow changes to climate change and human activities using the Budyko framework and a pre/post change-point analysis across various basins. The authors aim to assess the spatial and temporal variability of runoff responses and identify potential climate/human-induced alterations.

This topic is relevant and timely, particularly considering increasing concerns about anthropogenic pressures on the water cycle. The manuscript explores important concepts such as long-term water balance and hydroclimatic trends. However, several methodological and conceptual issues require attention before the manuscript can be considered for publication.

The manuscript has potential, but I believe major revisions are necessary to enhance its scientific rigor and overall clarity.

Major Comments

1. **Clarity and validity of the Budyko-based methodology**
   The manuscript applies the Budyko framework to assess climate and human contributions to runoff change. However, there are conceptual inconsistencies. In Line 570, the authors mention using monthly and annual runoff averages, but the Budyko framework is only valid for long-term (multi-year or decadal) averages. Applying it to short-term data undermines its theoretical foundation and may lead to incorrect attribution.
2. **Equations 4 and 5: Attribution logic needs revision**
   The logic behind Equations 4 and 5 is not clearly justified. It is unclear how Qafter - Qbefore is assumed to solely represent the impact of climate change. This approach appears to conflate climate and human influences. According to Wang and Hejazi (2011), both climate change and human activity can alter streamflow, but in distinct ways. Climate change can induce both horizontal (movement along the Budyko curve) and vertical (movement across the curve) components, while human activities tend to induce vertical changes only. Therefore, the contribution of direct human interventions should be computed first, and the residual change attributed to climate.

I strongly recommend the authors revise their attribution framework based on this more robust and widely accepted methodology.

3. **Evapotranspiration (Ea) Estimation and Sensitivity**
   The manuscript lacks justification for the selected method of estimating Ea. This is a critical variable in Budyko analysis, and different can yield significantly different results. The authors should:

- Justify the choice of Ea estimation approach,
- Provide Budyko plots showing how long-term P, PET, and Ea values fit the selected curves (see Zaerpour et al., 2024)—if the long-term averages do not fit well to the budyko cureve, the authors should consider use of other Ea estimation, etc.

4. **Correlation does not imply causation**
   The authors rely on **Spearman correlation** to identify key influencing factors in sub-catchments (Line 620). However, correlation analysis alone is insufficient for causal attribution and can be misleading, particularly in the presence of confounding variables or nonlinear interactions – See figure 7 at Zaerpour et al. (2024). This limitation should be explicitly discussed in the manuscript.

To strengthen the analysis, the authors could explore more advanced causal inference methods (e.g., PCMCI+), as demonstrated in recent hydrological applications (Zaerpour et al., 2024; Zaerpour et al., 2025). If these methods are not feasible to implement, the authors should revise the interpretation and language used to clearly state that correlation reflects association, not causation and discuss this limitation in the discussion.

5. **Trend Analysis method needs clarification**
   There is a discrepancy between the main text and supplementary material. While the main text refers to linear regression, the supplementary section mentions the Mann-Kendall trend test. The authors should clarify which method was used where, and why. These methods differ in assumptions and sensitivities.

6. **Use of multiple Budyko Curve types**
   The authors use four Budyko formulations, which is commendable. Including a visual comparison of observations over Budyko space would greatly improve transparency.

7. **Complexity of Period Division and Result Interpretation**
   The manuscript further subdivides the pre- and post-change periods into additional sub-periods, which complicates both the representation and interpretation of the results. The rationale for this additional division is not clearly justified. If possible, it would be more effective to present the results simply as “before” and “after” the detected change points. This would enhance the clarity of the findings and avoid overcomplicating the analysis without a strong conceptual justification for further periodization.

8. **Writing and Structural Clarifications**
   - **Line 59–60**: The phrase “have shifted upstream” is ambiguous—does this refer to seasonal shifts or geographic redistribution? Please clarify.

- **Line 61**: Suggest revising as: “An increasing trend may lead to greater reliance on …”
- **Line 73**: The sentence appears incomplete. Please revise for clarity.

Minor Comments

- **Line 51, 56, 74, and 556**: The following recent studies are highly relevant and should be cited when discussing human impacts on the water cycle and Budyko-based attribution:
  - Zaerpour et al. (2025) on agriculture and water-energy balance.
  - Hatami et al. (2024) on seasonal runoff variability and anthropogenic factors.
  - Liu et al. (2021) on spatial runoff changes and Budyko partitioning.
- **Equation References**: All equations should be accompanied by references or derivations to guide the reader and justify their inclusion.

References

- Wang, D., & Hejazi, M. (2011). Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research*, 47(10).
- Zaerpour, M., Hatami, S., Ballarin, A. S., Knoben, W. J., Papalexiou, S. M., Pietroniro, A., & Clark, M. P. (2024). Impacts of agriculture and snow dynamics on catchment water balance in the US and Great Britain. *Communications Earth & Environment*, 5(1), 733.
- Zaerpour, M., Hatami, S., Ballarin, A. S., Papalexiou, S. M., Pietroniro, A., & Nazemi, A. (2025). Agriculture’s impact on water–energy balance varies across climates. *Proceedings of the National Academy of Sciences*, 122(12), e2410521122.

RESPONSE TO REVIEWERS' COMMENTS

Dear Editor and reviewers,

We would like to express our sincere gratitude to the editor and reviewers for their insightful comments and constructive suggestions on our manuscript (COMMSENV-25-1244-T) entitled "**Climate change and human interventions induce larger runoff variability risks in the lower reaches of major river basin**". The provided comments have contributed substantially to improving the manuscript. In response to your comments point-by-point, we have carefully revised the paper and made substantial improvements. The reviewer's comments are displayed in italic font, while our response and revised text are shown in blue and black, respectively.

<u>Responses to Reviewer #1</u>

The manuscript explores the attribution of streamflow changes to climate change and human activities using the Budyko framework and a pre/post change-point analysis across various basins. The authors aim to assess the spatial and temporal variability of runoff responses and identify potential climate/human-induced alterations.

This topic is relevant and timely, particularly considering increasing concerns about anthropogenic pressures on the water cycle. The manuscript explores important concepts such as long-term water balance and hydroclimatic trends. However, several methodological and conceptual issues require attention before the manuscript can be considered for publication. The manuscript has potential, but I believe major revisions are necessary to enhance its scientific rigor and overall clarity.

Response: We sincerely appreciate the time you have taken to review our manuscript and offer insightful comments that significantly enhanced its quality. Based on your valuable comments, we have substantially revised and improved the manuscript. Specifically:

(1) We have re-quantified the contributions of climate change and human activities to runoff variation by using multi-year averages.

(2) We have reconstructed the attribution framework for runoff changes using the Budyko curve decomposition method.

(3) We have presented the concept diagram of the Budyko curve decomposition method, and the graph showing the relationship between the drought index and $(1-Q_{Sub}/P)$. Based on this, we have comprehensively elaborated on the principles, feasibility, and limitations of the runoff change attribution assessment method.
(4) We have incorporated the PCMCI+ causal discovery algorithm to better identify the effects of climatic and anthropogenic factors on runoff variations.
(5) We have clarified the trend analysis method and the long-term time-series change-point detection method.
(6) We have further conducted change-point detection on runoff data from different time periods.
(7) We have updated the references and polished the writing of this manuscript.

Major Comments

Comment 1: Clarity and validity of the Budyko-based methodology

The manuscript applies the Budyko framework to assess climate and human contributions to runoff change. However, there are conceptual inconsistencies. In Line 570, the authors mention using monthly and annual runoff averages, but the Budyko framework is only valid for long-term (multi-year or decadal) averages. Applying it to short-term data undermines its theoretical foundation and may lead to incorrect attribution.

Response 1: Thank you for helping us identify this issue. We have reviewed literature on the Budyko water-energy balance theory[1,2,3]. This theory assumes that soil water storage remains essentially unchanged under long-term multi-year averages[1,4]. This assumption may not hold when using annual averages or short-term data, potentially leading to incorrect attributions. Therefore, we have adopted multi-year averages to re-quantify the contributions of climate change and human activities to runoff variations. We have also revised the relevant figures (Figures 6 and 7) and tables (Supplementary Tables 3–5) in the manuscript.

References:

1. Liu, J. & You, Y. The Roles of catchment characteristics in precipitation partitioning within the Budyko framework. *Journal of Geophysical Research: Atmospheres* **126**, doi:10.1029/2021jd035168 (2021).

2. Dey, P. & Mishra, A. Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions. *Journal of Hydrology* **548**, 278-290, doi:10.1016/j.jhydrol.2017.03.014 (2017).
3. Budyko, M. I. *Climate and Life*, Vol **508** (Academic, 1974).
4. Luan, J. et al. Evaluating the uncertainty of eight approaches for separating the impacts of climate change and human activities on streamflow. *Journal of Hydrology* **601**, doi:10.1016/j.jhydrol.2021.126605 (2021).

Revised Manuscript LL 230-241:

The impacts of climate change and human activities on annual and monthly runoff contributions vary spatially across sub-catchments and temporally across periods (Fig. 6). From Period I to Period II, the multi-year average runoff reduction along the Yellow River's mainstem hydrological stations increases from upstream TNH (47.92 $m^3 s^{-1}$) to downstream LJ (733.05 $m^3 s^{-1}$). Notably, 90% of sub-catchments (except S5 and S18) exhibiting negative contributions (Fig. 6a). Additionally, the percentage of climate change's contribution to runoff reduction at each hydrological station, compared to the total reduction (i.e., the runoff reduction at the LJ station), ranges from -8.6% to 7.1%. In contrast, the impact of human activities ranges from 15.2% to 92.9%. These results indicate that anthropogenic interference dominates the changes in the Yellow River's runoff. Notably, the increased precipitation in headwater catchments reduces the impact of climate change on runoff decline across the entire watershed.

Revised Manuscript LL 242-250:

When divided into four sub-periods, from Period 1 to Period 2 and then to Period 3, the runoff contribution for the entire basin decreases by 538.19 $m^3 s^{-1}$ and 586.35 $m^3 s^{-1}$. Climate change and human disturbances account for 18.9% versus 81.1% of the first decrease, and 30% versus 70% of the second decrease, respectively. Notably, 80% of the sub-catchments experience reductions (Fig. 6b and 6c). From Period 3 to Period 4, the runoff contribution for the entire basin increases by 252.94 $m^3 s^{-1}$, but 50% of sub-catchments show a decrease in runoff contribution (Fig. 6d). Climate change and human disturbances account for 138.7% and -38.7%, respectively. This indicates that the overall increase in runoff contribution results solely from climate change.

Revised Manuscript LL 660-667:

Therefore, based on the decomposition method illustrated in Supplementary Fig. 6c, the formula for calculating the direct contribution of human activities to catchment runoff variation during the change period can be derived as follows:

$$\Delta Q_h = P_2(AE_2'/P_2 - Q_2/P_2) - P_1(AE_1'/P_1 - Q_1/P_1) \quad (8)$$

where Q_1 and Q_2 respectively represent the multi-year averages of the runoff contributions from each sub-catchment during the reference period and change period. AE_1'/P_1 and AE_2'/P_2 respectively represent the theoretical evapotranspiration ratios corresponding to the aridity index for the reference period and the change period.

Revised Figures: Fig. 6 and Fig. 7

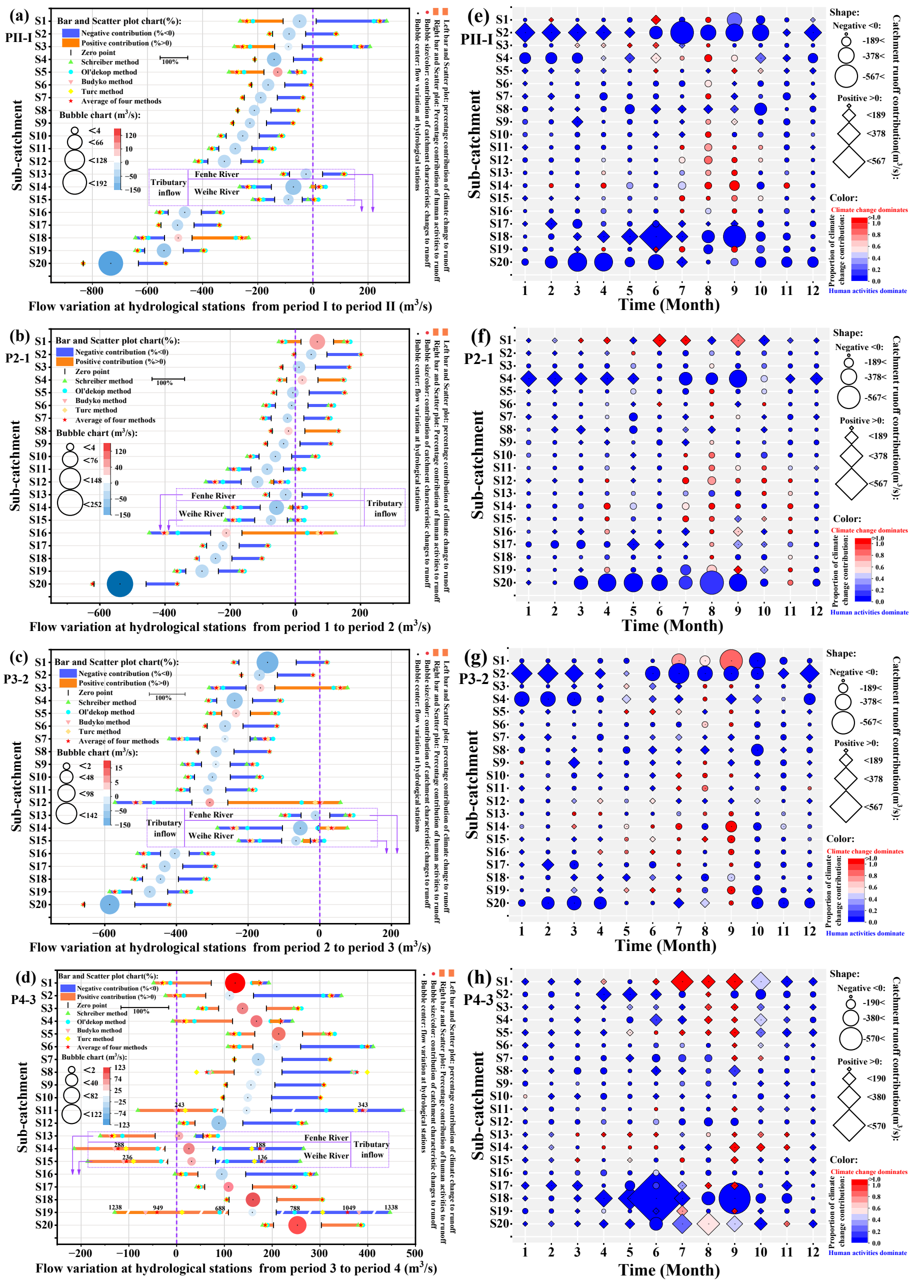


Fig. 6: The annual and monthly contribution rates of climate change and human activities to the changes in runoff contribution volumes in each sub-catchment. The multi-year average annual scale runoff contribution volume changes (bubble chart) for upstream and downstream sub-catchments from period I to period II **(a)**, period 1 to period 2 **(b)**, period 2 to period 3 **(c)**, and period 3 to period 4 **(d)**, the percentage contributions (%) of climate change and human activities to the changes in runoff contribution volumes (bar chart and scatter plot), and the flow volume changes at the corresponding hydrological stations at the outlets of each sub-

catchment (center points of bubbles). The multi-year average monthly scale runoff contribution volume changes (shape and size of points) for upstream and downstream sub-catchments from period I to period II **(e)**, period 1 to period 2 **(f)**, period 2 to period 3 **(g)**, and period 3 to period 4 **(h)**, and the proportion of the contribution of climate change to the total changes in runoff contribution volume (color of points).

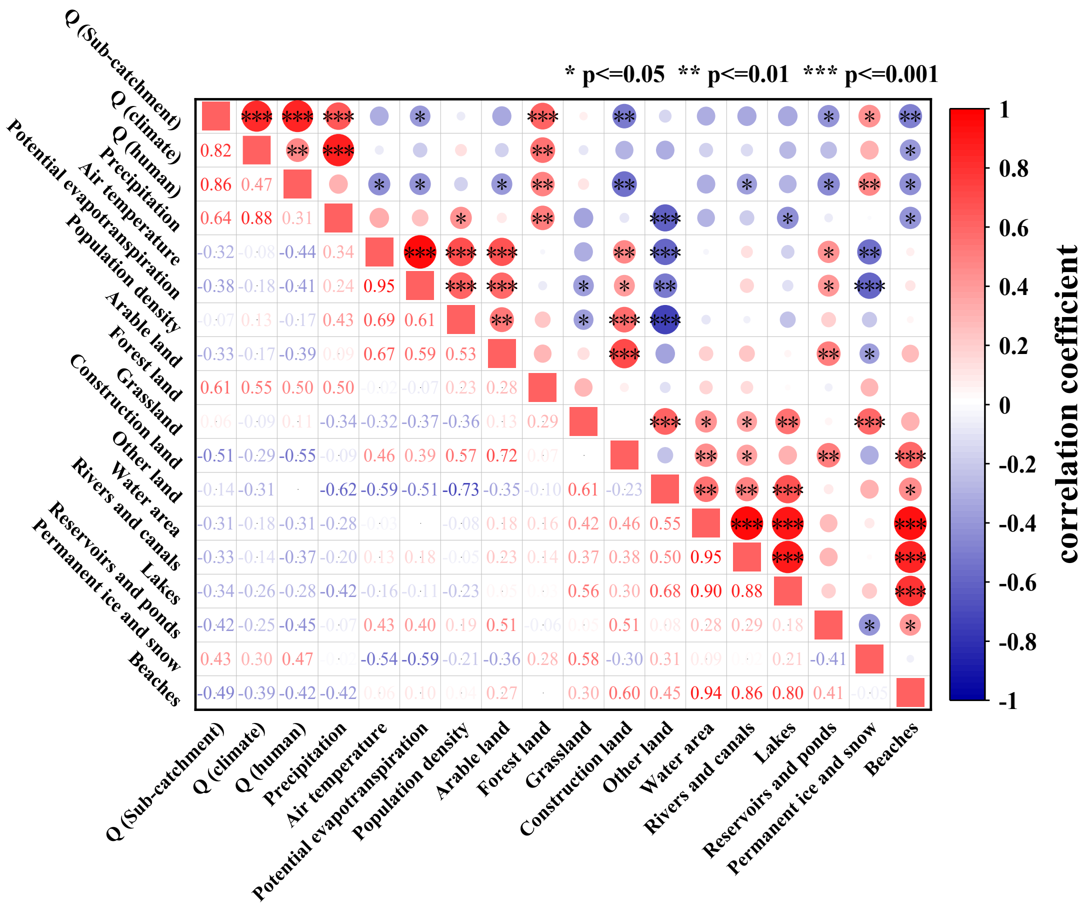


Fig. 7: The correlation relationship between runoff contribution volumes of sub-catchments, changes in runoff contributions caused by climate change and human activities, and factors such as air temperature, precipitation, potential evapotranspiration, population density, and various land use types. The color and size of the circles represent the correlation coefficients between variables, with red indicating positive correlation and blue indicating negative correlation. Asterisks denote significance levels (* for $p \leq 0.05$, ** for $p \leq 0.01$, *** for $p \leq 0.001$).

Comment 2: Equations 4 and 5: Attribution logic needs revision

The logic behind Equations 4 and 5 is not clearly justified. It is unclear how Qafter - Qbefore is assumed to solely represent the impact of climate change. This approach appears to conflate climate and human influences. According to Wang and Hejazi (2011), both climate change and human activity can alter streamflow, but in distinct ways. Climate change can induce both horizontal (movement along the Budyko curve) and vertical (movement across the curve) components, while human activities tend to induce vertical changes only. Therefore, the contribution of direct human interventions should be computed first, and the residual change attributed to climate.

I strongly recommend the authors revise their attribution framework based on this more robust and widely accepted methodology.

Response 2: We sincerely appreciate your constructive comments on our attribution analysis framework, as well as the references you provided. Based on these references[2,3,4,5], we have introduced a more robust Budyko curve decomposition method to quantify the impact of climate change and human activities on runoff changes. Additionally, we have comprehensively revised and improved the runoff change attribution analysis framework proposed in this study. Specifically:

(1) In the resubmitted manuscript, we have re-defined the periods as follows:

- The period before the change point is defined as the reference period.
- The period after the change point is defined as the change period.
- Correspondingly, Q_{before} in the first manuscript has been replaced with Q_1, and Q_{after} has been replaced with Q_2.

(2) It should be noted that the watershed conditions during the reference period do not represent completely natural states[2,5]. Therefore, many studies have introduced surface characteristic parameters to reconstruct the Budyko curve equation. However, deviations may still exist between the observed values (PET/P, $1-Q_{Sub}/P$) and these reconstructed curves[2,3,4,5]. Additionally, our study focuses on comparing the contributions of climate change and human activities to runoff variation during the chang period relative to the reference period. Therefore, we have re-define the human activity contribution to runoff change during the chang period compared to the reference period as: the difference between the [Vertical deviation of Point B

(change period) from the Budyko curve] and the [Vertical deviation of Point A (reference period) from the Budyko curve].

(3) This study adopts a non-parametric approach to disentangle the impacts of climate change and human activities on runoff variation, while using multiple Budyko equations to ensure result reliability.

The above comments have been elaborated in the Methods section.

References:

2. Dey, P. & Mishra, A. Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions. *Journal of Hydrology* **548**, 278-290, doi:10.1016/j.jhydrol.2017.03.014 (2017).
3. Budyko, M. I. *Climate and Life*, Vol **508** (Academic, 1974).
4. Luan, J. et al. Evaluating the uncertainty of eight approaches for separating the impacts of climate change and human activities on streamflow. *Journal of Hydrology* **601**, doi:10.1016/j.jhydrol.2021.126605 (2021).
5. Wang, D. & Hejazi, M. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research* **47**, doi:10.1029/2010wr010283 (2011).

Revised Manuscript LL 574-679:

Decompose the contributions of climate change and human activities

Budyko demonstrates that the evaporation ratio (AE/P) of a basin is primarily governed by the ratio of potential evapotranspiration (PET) to precipitation (P), which is denoted as the aridity index ($\varphi = PET/P$). He further proposes corresponding water-energy balance curve equations for basins[84]. However, other factors, such as vegetation, soil water storage, and rainfall seasonality, affect precipitation partitioning, resulting in scattered observations around the Budyko curve[28,30]. Consequently, researchers have proposed various forms of water-energy balance equations tailored to different watershed characteristics[17,19,20]. Furthermore, deviations between specific catchments and the Budyko curve have been used to evaluate the impact of basin attributes[28,29]. The broad applicability of Budyko water-energy balance framework has been extensively validated[19,42]. Building on this, we employ the detection of change points combined with the water-energy coupling equation to quantitatively assess the contribution of climate change and human activities to runoff variation in each sub-catchment. Given the significant anthropogenic influences and regional heterogeneity among sub-catchments, changes in evapotranspiration due to altered basin properties may be closely linked to human activities[42,53]. We therefore apply four non-parametric Budyko curves (Equation 3) to compare upstream and downstream sub-catchments. These non-parametric curves exhibit strong robustness in eliminating uncertainties associated with parameterization and capturing complex hydrological responses across heterogeneous watersheds[28,29].

$$\frac{AE'}{P} = f(\varphi) = \begin{cases} (1 - e^{-\varphi}) & \text{Schreiber}^{85} \\ \varphi \times tanh(1/\varphi) & \text{Ol'dekop}^{86} \\ \sqrt{\varphi \times (1 - e^{-\varphi}) \times tanh(1/\varphi)} & \text{Budyko}^{84} \\ \left(1/\sqrt{1 + \varphi^{-2}}\right) & \text{Turc}^{87} \end{cases} \tag{3}$$

where AE'/P is the theoretical evapotranspiration ratio on the Budyko curve corresponding to the aridity index. φ is the simple drought index, i.e., (PET/P).

In this study, we employ a decomposition method to separate the impacts of climate change and human activities on runoff variation[17,30,45], as illustrated in Supplementary Fig. 6a. In this study, the impact of human activities on runoff excludes indirect effects induced by anthropogenic climate change[45]. Specifically, we hypothesize that combined human activities and climate change shift the relationship between aridity index and evaporation ratio in the catchment from Point A (PET_1/P_1, AE_1/P_1) in the reference period to Point B (PET_2/P_2, AE_2/P_2) in the changed period. Under the sole influence of climate change, the aridity index-evaporation ratio relationship would follow the Budyko curve, transitioning from Point A to Point C (PET_2/P_2, AE_2'/P_2), which shares the same aridity index as Point B. Direct human activities then drive the relationship from Point C to Point B. This reveals that climate change affects both horizontal and vertical components of runoff variation in the catchment, while direct human activities only induce vertical changes in runoff[30,45]. Under long-term average conditions, where soil water storage variations are negligible[17], runoff can be expressed as a function of precipitation and the evaporation ratio:

$$Q_{Sub} = P(1 - AE/P) \tag{4}$$

Consequently, the contribution of human activities to runoff variation can be calculated as follows:

$$\Delta Q_h = P_2(AE_2'/P_2 - AE_2/P_2) \tag{5}$$

For a given region, differences in multi-year average streamflow (ΔQ_{Sub}) between the change period (Q_2) and reference period (Q_1) at hydrological stations result from the combined effects of climate change (ΔQ_c) and human activities (ΔQ_h):

$$\Delta Q_{Sub} = Q_2 - Q_1 = \Delta Q_c + \Delta Q_h \quad (6)$$

Consequently, the impacts of climate change on runoff variation can be expressed as follows:

$$\Delta Q_c = \Delta Q_{Sub} - \Delta Q_h \quad (7)$$

However, the focus of this study is to analyze the changes in runoff during the change period compared to the reference period, where the catchment area in the reference period is not in a pristine natural state. Therefore, many studies have reconstructed the Budyko curve equation based on the physical characteristics of the reference period catchment (Supplementary Fig. 6b), which may be a good practice for investigating the variations of individual catchments over different periods[19,21,25]. However, this study emphasizes the analysis of the interconnectedness between upstream and downstream catchments. Developing Budyko curve equations for each catchment would introduce greater uncertainties into subsequent analyses while compromising the comparability across catchments [19]. Consequently, this study adopts non-parametric curve equations to decompose the impacts of climate change and human activities on runoff variations. Additionally, multiple non-parametric water-energy balance curve equations are employed to ensure the reliability of the results.

In addition, the runoff during the reference period is also affected by anthropogenic disturbances[18,88,89], as shown in Supplementary Fig. 6c. Therefore, it is necessary to subtract the deviation between the reference period and the Budyko curve to reduce the discrepancies in anthropogenic impacts on runoff variation across different catchments[22]. Furthermore, the mid-to-downstream catchments in this study receive and utilize upstream external water resources. Under the assumption of long-term multi-year average conditions, the water loss through climatic evaporation or evapotranspiration from these external resources and reservoir regulation is negligible[20]. This portion of water represents an additional contribution to runoff changes due to human activities, distinct from the evapotranspiration losses caused by human activities[17]. Consequently, after subtracting this water volume, the actual evapotranspiration Point B' in these catchments still adheres to the assumptions of the Budyko water-energy balance theory. The Budyko curve and decomposition method employed in this study remain applicable to these catchments. Thus, the shift in the relationship between aridity index and evaporation ratio from Point C to Point B still reflects the impact of human activities on runoff variation. The actual evapotranspiration Point B' serves as an intermediate variable that cancels out when calculating the total contribution of human activities to runoff changes. Therefore, the upstream inflow recharge and reservoir regulation may cause the relationship between the drought index and evaporation ratio in the sub-catchment to deviate from the water supply control line of the Budyko framework, entering the blue-shaded region beyond this boundary (as shown in Supplementary Fig. 6d and Supplementary Fig. 7, where $1 - Q_{Sub}/P > 1$).

Therefore, based on the decomposition method illustrated in Supplementary Fig. 6c, the formula for calculating the direct contribution of human activities to catchment runoff variation during the change period can be derived as follows:

$$\Delta Q_h = P_2(AE_2'/P_2 - Q_2/P_2) - P_1(AE_1'/P_1 - Q_1/P_1) \tag{8}$$

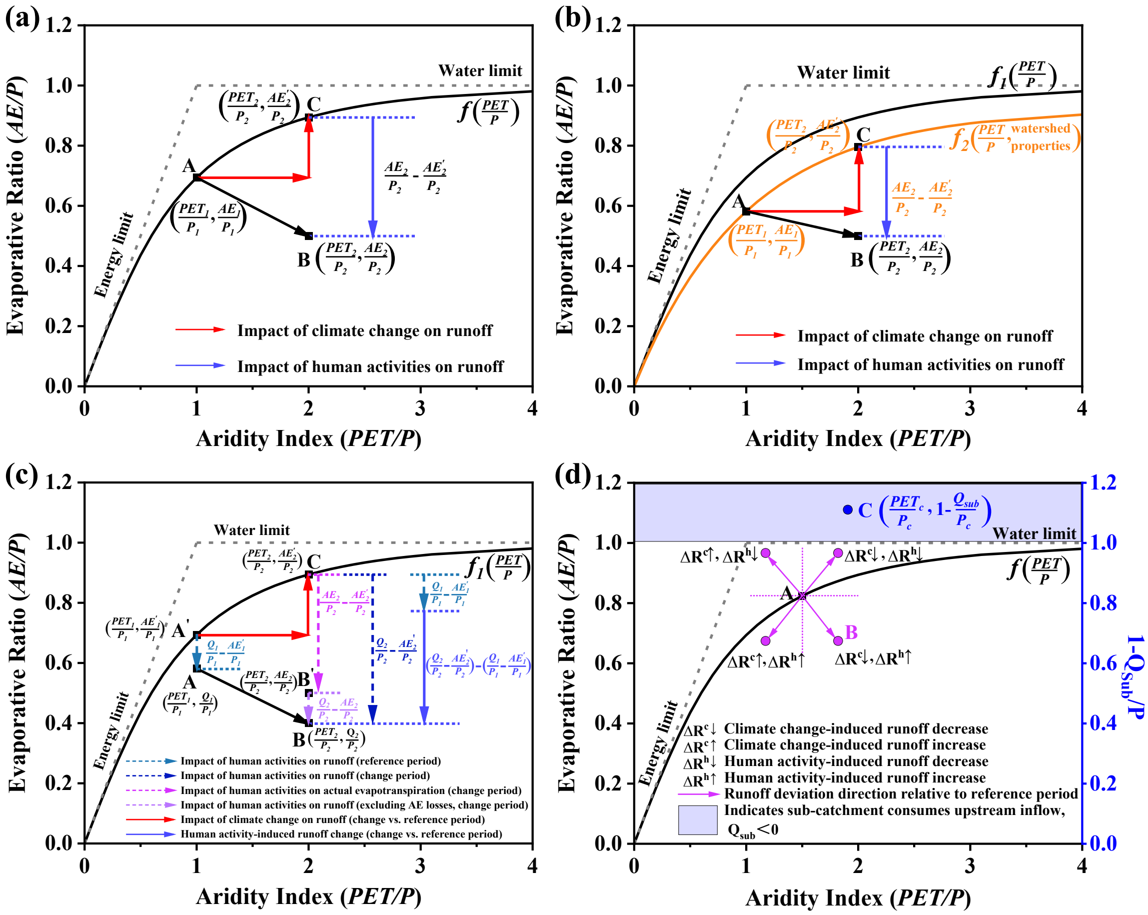
where Q_1 and Q_2 respectively represent the multi-year averages of the runoff contributions from each sub-catchment during the reference period and change period. AE_1'/P_1 and AE_2'/P_2 respectively represent the theoretical evapotranspiration ratios corresponding to the aridity index for the reference period and the change period. Similarly, the contribution of climate change in the change period relative to the reference period to the runoff variation in the catchment area can be derived from Equation (7). Then, the contribution rates of climate change and human activities to the variation in runoff of the sub-catchment can be calculated using the following formula:

$$\omega_h = \frac{\Delta Q_h}{|\Delta Q_{Sub}|} \times 100\% \tag{9}$$

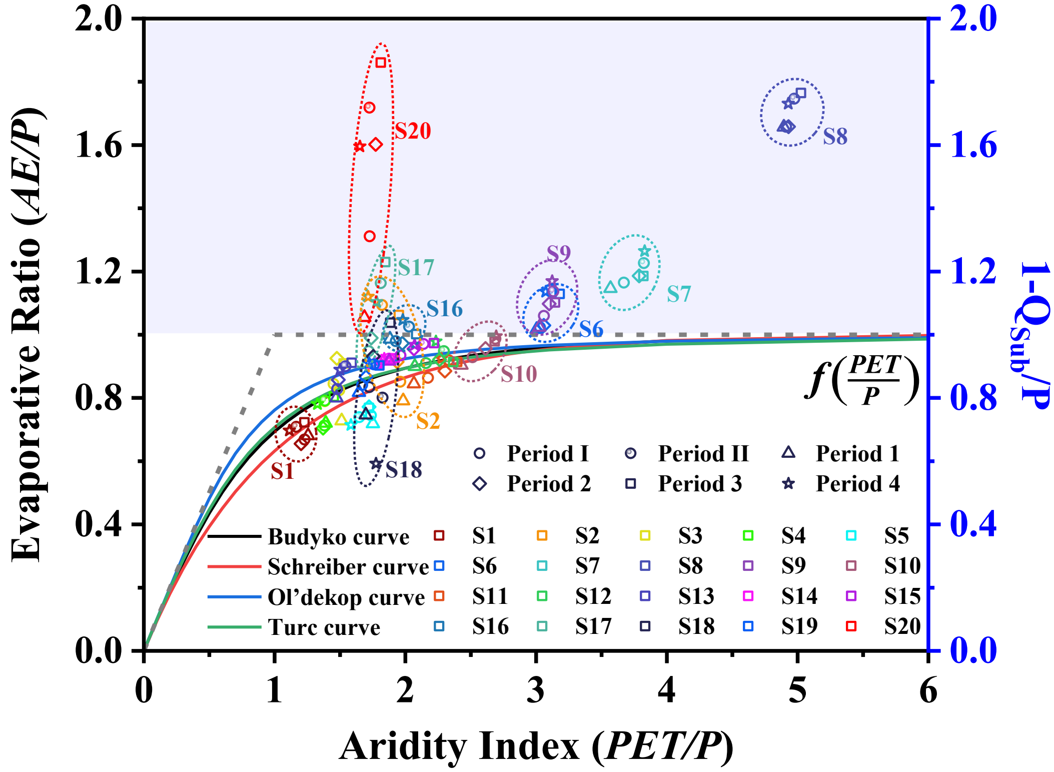
$$\omega_c = \frac{\Delta Q_c}{|\Delta Q_{Sub}|} \times 100\% \tag{10}$$

where ω_c and ω_h are the percentage of the change in runoff contribution caused by climate change and human activities to the total change in runoff contribution of the sub-catchment, respectively; $\omega_c > 0$ ($\omega_h > 0$) indicates a positive contribution from climate change (human activities), increasing the runoff contribution of the watershed[30,45]. Otherwise, it is a negative contribution, as shown in Supplementary Fig. 6d.

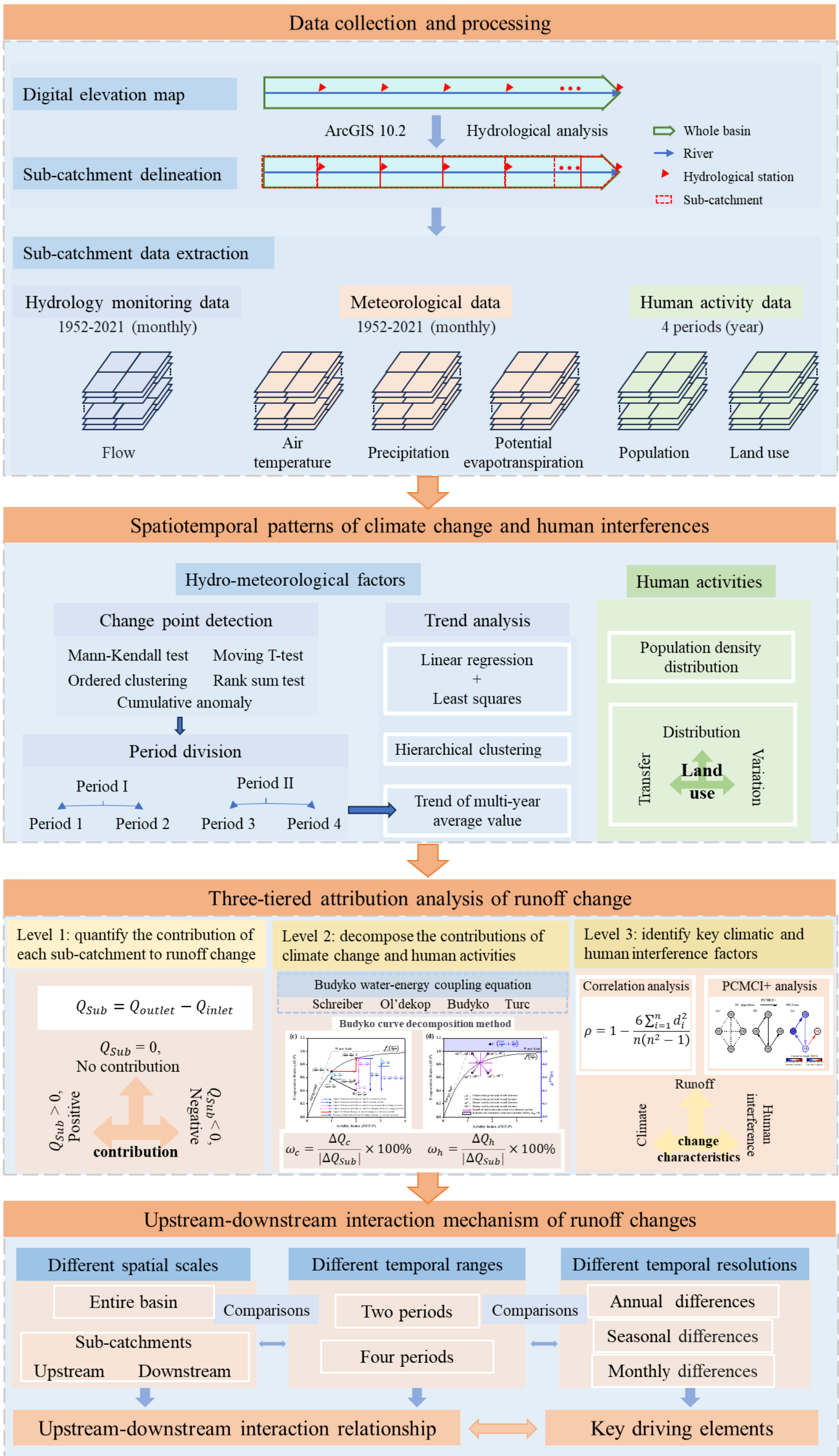
Revised Supplementary Figures: Supplementary Fig. 6-7 and Supplementary Fig. 3



Supplementary Fig. 6: Overview of methods for decomposing the Budyko water-energy balance curve to quantify the impacts of climate change and human activities on runoff variation. **(a)** Traditional non-parametric Budyko curve decomposition method; **(b)** Parametric water-energy balance curve decomposition method; **(c)** The non-parametric Budyko curve decomposition method comparing change periods to reference periods in this study, which incorporates the impact of external water resource contributions (excluding evapotranspiration losses caused by human activities) on runoff changes; **(d)** Characteristics of climate change and human activity impacts on runoff coefficient ($R = Q_{Sub}/P$), with anomalous zones (light blue areas) showing long-term runoff contribution amounts and precipitation relationships in midstream/downstream sub-catchments receiving external water resources.



Supplementary Fig. 7: The long-term mean annual runoff contribution and precipitation relationship data for each studied sub-catchment within the Budyko water-energy balance framework. Point shapes represent different periods, while colors denote different sub-catchments. Points within the light blue zone indicate sub-catchments with negative runoff contributions to the main river, representing either severe water scarcity or reservoir construction in these sub-catchments that utilize or store exogenous water resources from upstream areas.



Supplementary Fig. 3: The overall framework of the research process and the three-tiered attribution analysis method for streamflow variation.

Comment 3: Evapotranspiration (Ea) Estimation and Sensitivity

The manuscript lacks justification for the selected method of estimating Ea. This is a critical variable in Budyko analysis, and different can yield significantly different results.

The authors should:

o *Justify the choice of Ea estimation approach,*

o *Provide Budyko plots showing how long-term P, PET, and Ea values fit the selected curves (see Zaerpour et al., 2024)—if the long-term averages do not fit well to the budyko cureve, the authors should consider use of other Ea estimation, etc.*

Response 3: Thank you for your comments. We have comprehensively elaborated on the justification, feasibility, and limitations of the runoff change attribution assessment method employed in this study. To enhance the interpretability of runoff changes, we have provided a conceptual diagram of the Budyko curve decomposition method[2,5]. Additionally, we have visualized the distribution maps of (PET/P, $1-Q_{Sub}/P$) for each sub-catchment during the change period compared to the reference period.

However, when (PET/P, $1-Q_{Sub}/P$) align more closely with the Budyko curve, it indicates that human activities during the change period have minimal variation[5]. In such cases, human activities exert negligible influence on runoff or actual evapotranspiration. Therefore, the justification of the actual evaporation estimation method cannot be solely determined based on the fitting situation of (PET/P, $1-Q_{Sub}/P$) with the Budyko curve[5,6].

Furthermore, Budyko and other researchers[4,5,6] have demonstrated that factors such as vegetation, soil moisture content, and rainfall seasonality can also influence precipitation partitioning. These factors will cause the observed data points to be scattered around the Budyko curve[6,7]. Therefore, greater deviations between (PET/P, $1-Q_{Sub}/P$) and the Budyko curve indicate stronger human activity impacts on runoff changes.

Specifically, we have quantified the contributions of human activities to runoff variations in sub-catchments by decomposing the vertical component of the Budyko curve. This approach bears methodological similarity to Zaerpour et al. (2024), who assessed the impacts of snow fraction or irrigation on runoff changes by analyzing deviations between specific watersheds and the Budyko curve[6]. The distinction of our study lies in the application of change-point detection to demarcate change periods.

Moreover, this study employs the non-parametric Budyko water-energy balance curve theory to quantify the impacts of climate change and human activities on runoff variations for the following reasons:

(1) The framework is based on a water-energy balance curve equation constructed from a global dataset of extensive observations. It has been widely applied in attribution analyses of runoff changes across basins with precipitation gradients ranging from 35 to 2,980 millimeters and drainage areas from 1 to 6 million square kilometers, including numerous studies in the Yellow River Basin[8,9]. The applicability of the Budyko framework has been thoroughly validated.

(2) The greatest characteristic of Budyko theory lies in its capacity to calculate evapotranspiration under specific basin conditions during a given period, when the influence of human activities is minimal[2]. When anthropogenic disturbances occur, the relationship between the aridity index and evapotranspiration shifts vertically within the Budyko framework. The greater the deviation from the Budyko curve, the more significant the human activity is. Additionally, the Budyko curve is derived from observational data across numerous real-world basins, offering robust explanations for cases where watersheds deviate from the curve. Building on this, many studies have decomposed and quantified the effects of climate change and human activities on runoff variations by analyzing deviations from the Budyko curve. Although the Budyko curve decomposition method inherently involves some errors, its advantages have led to widespread adoption. This study leverages the established rationality, feasibility, and broad applicability of the Budyko water-energy balance curve decomposition method.

(3) This study prioritizes in analyzing upstream-downstream interactions. Reconstructing different attribution models for each sub-catchment would exacerbate uncertainty quantification. Therefore, we employ multiple non-parametric water-energy balance curves to ensure result reliability.

Indubitably, the non-parametric Budyko curve decomposition method employed herein has limitations. For example, non-parametric Budyko curves overlook the impact of differences in underlying surface characteristics across sub-catchments on the attribution of runoff variations. However, it provides insights into the interplay of runoff changes among upstream and downstream sub-catchments under combined climate change and human activity pressures. The justification, reasonableness, and limitations of the Budyko water-energy balance curve decomposition approach are revised in the Methods and Discussion sections.

References:

2. Dey, P. & Mishra, A. Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions. *Journal of Hydrology* **548**, 278-290, doi:10.1016/j.jhydrol.2017.03.014 (2017).
4. Luan, J. et al. Evaluating the uncertainty of eight approaches for separating the impacts of climate change and human activities on streamflow. *Journal of Hydrology* **601**, doi:10.1016/j.jhydrol.2021.126605 (2021).
5. Wang, D. & Hejazi, M. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research* **47**, doi:10.1029/2010wr010283 (2011).
6. Zaerpour, M. et al. Impacts of agriculture and snow dynamics on catchment water balance in the U.S. and Great Britain. *Communications Earth & Environment* **5**, doi:10.1038/s43247-024-01891-w (2024).
7. Zaerpour, M., Hatami, S., Ballarin, A. S., Papalexiou, S. M., Pietroniro, A., & Nazemi, A. Agriculture's impact on water–energy balance varies across climates. *P Natl Acad Sci USA*, **122**(12) e2410521122 (2025).
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9. Wang, W., Zhang, Y. & Tang, Q. Impact assessment of climate change and human activities on streamflow signatures in the Yellow River Basin using the Budyko hypothesis and derived differential equation. *Journal of Hydrology* **591**, doi:10.1016/j.jhydrol.2020.125460 (2020).

Revised Manuscript LL 575-594:

Budyko demonstrates that the evaporation ratio (AE/P) of a basin is primarily governed by the ratio of potential evapotranspiration (PET) to precipitation (P), which is denoted as the aridity index ($\varphi = PET/P$). He further proposes corresponding water-energy balance curve equations for basins[84]. However, other factors, such as vegetation, soil water storage, and rainfall seasonality, affect precipitation partitioning, resulting in scattered observations around the Budyko curve[28,30]. Consequently, researchers have proposed various forms of water-energy balance equations tailored to different watershed characteristics[17,19,20]. Furthermore, deviations between specific catchments and the Budyko curve have been used to evaluate the impact of basin attributes[28,29]. The broad applicability of Budyko water-energy balance framework has been extensively validated[19,42]. Building on this, we employ the detection of change points combined with the water-energy coupling equation to quantitatively assess the contribution of climate change and human activities to runoff variation in each sub-catchment. Given the significant anthropogenic influences and regional heterogeneity among sub-catchments, changes in evapotranspiration due to altered basin properties may be closely linked to human activities[42,53]. We therefore apply four non-parametric Budyko curves (Equation 3) to compare upstream and downstream sub-catchments. These non-parametric curves exhibit strong robustness in eliminating uncertainties associated with parameterization and capturing complex hydrological responses across heterogeneous watersheds[28,29].

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However, the focus of this study is to analyze the changes in runoff during the change period compared to the reference period, where the catchment area in the reference period is not in a pristine natural state. Therefore, many studies have reconstructed the Budyko curve equation based on the physical characteristics of the reference period catchment (Supplementary Fig. 6b), which may be a good practice for investigating the variations of individual catchments over different periods[19,21,25]. However, this study emphasizes the analysis of the interconnectedness between upstream and downstream catchments. Developing Budyko curve equations for each catchment would introduce greater uncertainties into subsequent analyses while compromising the comparability across catchments [19]. Consequently, this study adopts non-parametric curve equations to decompose the impacts of climate change and human activities on runoff variations. Additionally, multiple non-parametric water-energy balance curve equations are employed to ensure the reliability of the results.

In addition, the runoff during the reference period is also affected by anthropogenic disturbances[18,88,89], as shown in Supplementary Fig. 6c. Therefore, it is necessary to subtract the deviation between the reference period and the Budyko curve to reduce the discrepancies in anthropogenic impacts on runoff variation across different catchments[22]. Furthermore, the mid-to-downstream catchments in this study receive and utilize upstream external water resources. Under the assumption of long-term multi-year average conditions, the water loss through climatic evaporation or evapotranspiration from these external resources and reservoir regulation is negligible[20]. This portion of water represents an additional contribution to runoff changes due to human activities, distinct from the evapotranspiration losses caused by human activities[17].

Consequently, after subtracting this water volume, the actual evapotranspiration Point B' in these catchments still adheres to the assumptions of the Budyko water-energy balance theory. The Budyko curve and decomposition method employed in this study remain applicable to these catchments. Thus, the shift in the relationship between aridity index and evaporation ratio from Point C to Point B still reflects the impact of human activities on runoff variation. The actual evapotranspiration Point B' serves as an intermediate variable that cancels out when calculating the total contribution of human activities to runoff changes. Therefore, the upstream inflow recharge and reservoir regulation may cause the relationship between the drought index and evaporation ratio in the sub-catchment to deviate from the water supply control line of the Budyko framework, entering the blue-shaded region beyond this boundary (as shown in Supplementary Fig. 6d and Supplementary Fig. 7, where $1 - Q_{Sub}/P > 1$).

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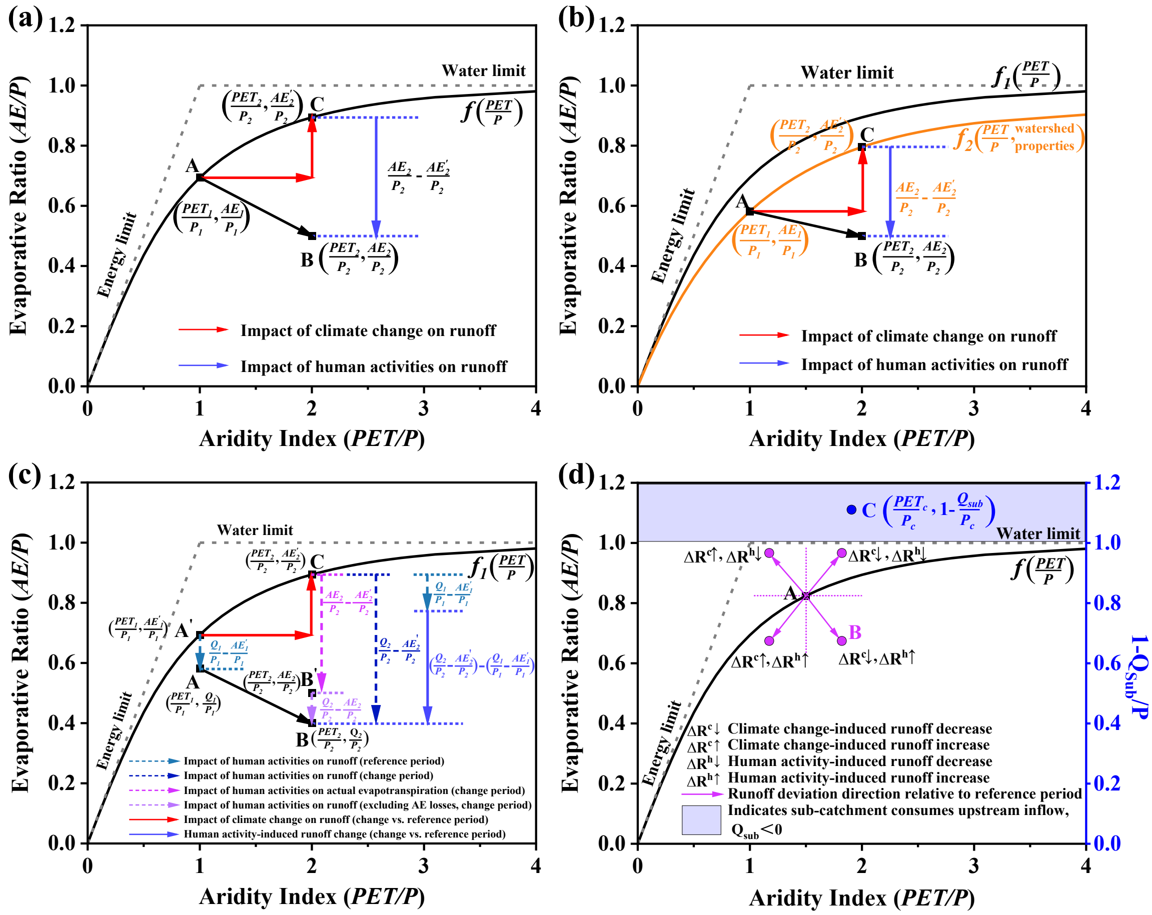
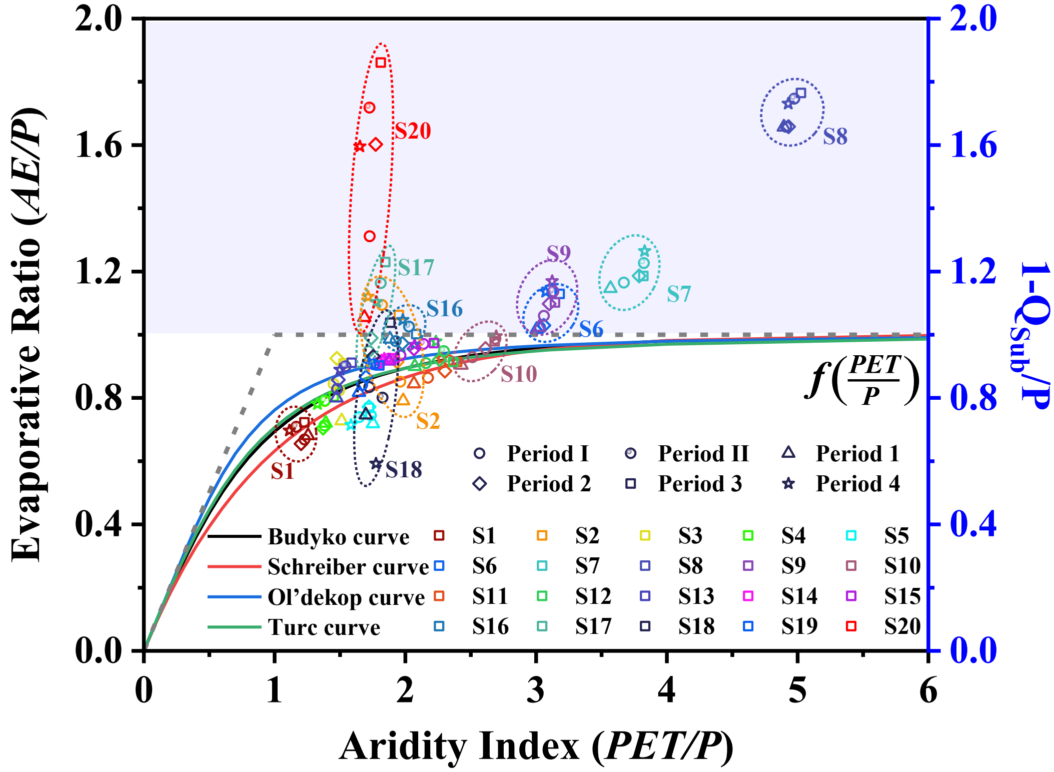
Notably, our research assumes that water resources are transported between sub-basins solely through the main river channel[73]. Thus, the interactions between sub-basins may be more complex and interconnected. Additionally, the catchment range of each region does not remain fixed over the past 70 years[1]. The attribution decomposition method for runoff variation neither accounts for the differences in surface characteristics across distinct sub-watersheds nor considers the intricate effects of upstream inflow reception and utilization on the actual evapotranspiration in mid-lower sub-basin regions[17,19,22,25,30]. To clarify the interactions between sub-catchments, we unify the variation periods of meteorological and hydrological time series data[74]. These factors increase the uncertainty in decomposing the contributions of climate change and human activities, but do not affect the key conclusions in this study. Furthermore, due to the lack of continuous data on population density, land use, and groundwater resource changes at the third level of attribution analysis, our study does not accurately quantify the contributions of different types of human activities to runoff changes.

Revised Supplementary Figures: Supplementary Fig. 6-7



Supplementary Fig. 6: Overview of methods for decomposing the Budyko water-energy balance curve to quantify the impacts of climate change and human activities on runoff variation. (a) Traditional non-parametric Budyko curve decomposition method; **(b)** Parametric water-energy balance curve decomposition method; **(c)** The non-parametric Budyko curve decomposition method comparing change periods to reference periods in this study, which incorporates the impact of external water resource contributions (excluding evapotranspiration losses caused by human activities) on runoff changes; **(d)** Characteristics of climate change and human activity impacts on runoff coefficient ($R = Q_{Sub}/P$), with anomalous zones (light blue areas) showing long-term runoff contribution amounts and precipitation relationships in midstream/downstream sub-catchments receiving external water resources.



Supplementary Fig. 7: The long-term mean annual runoff contribution and precipitation relationship data for each studied sub-catchment within the Budyko water-energy balance framework. Point shapes represent different periods, while colors denote different sub-catchments. Points within the light blue zone indicate sub-catchments with negative runoff contributions to the main river, representing either severe water scarcity or reservoir construction in these sub-catchments that utilize or store exogenous water resources from upstream areas.

Comment 4: Correlation does not imply causation

The authors rely on Spearman correlation to identify key influencing factors in sub-catchments (Line 620). However, correlation analysis alone is insufficient for causal attribution and can be misleading, particularly in the presence of confounding variables or nonlinear interactions – See figure 7 at Zaerpour et al. (2024). This limitation should be explicitly discussed in the manuscript.

To strengthen the analysis, the authors could explore more advanced causal inference methods (e.g., PCMCI+), as demonstrated in recent hydrological applications (Zaerpour et al., 2024;

Zaerpour et al., 2025). If these methods are not feasible to implement, the authors should revise the interpretation and language used to clearly state that correlation reflects association, not causation and discuss this limitation in the discussion.

Response 4: We are truly grateful for your constructive comments and the valuable references you provided (Zaerpour et al., 2024; Zaerpour et al., 2025) [6,7]. Based on your comments, we have introduced the PCMCI+ causal discovery algorithm into this study to analyze the causal relationships between runoff contribution and key climatic factors in each sub-catchment. Building on this, we further:

- Investigated how human activities affect the causal linkages between climatic factors and the runoff contribution of sub-catchment.
- Identified the dominant drivers of runoff variation in each sub-catchment under the combined effects of climatic and anthropogenic influences.
- Confirmed that the impact of climate change on runoff has a lag effect.

The specific modifications are as follows:

References:

6. Zaerpour, M. et al. Impacts of agriculture and snow dynamics on catchment water balance in the U.S. and Great Britain. *Communications Earth & Environment* **5**, doi:10.1038/s43247-024-01891-w (2024).
7. Zaerpour, M., Hatami, S., Ballarin, A. S., Papalexiou, S. M., Pietroniro, A., & Nazemi, A. Agriculture's impact on water–energy balance varies across climates. *P Natl Acad Sci USA*, **122**(12) e2410521122 (2025).

Revised Manuscript LL 692-725: Methodology section

In this study, we evaluate the correlation between the runoff contribution of each sub-catchment and various climatic and human interference factors using the Spearman correlation[33] in OriginPro 2024 software:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \quad (11)$$

where ρ represents the Spearman correlation coefficient, d_i represents the difference in ranks for each pair of variables, and n is the sample size.

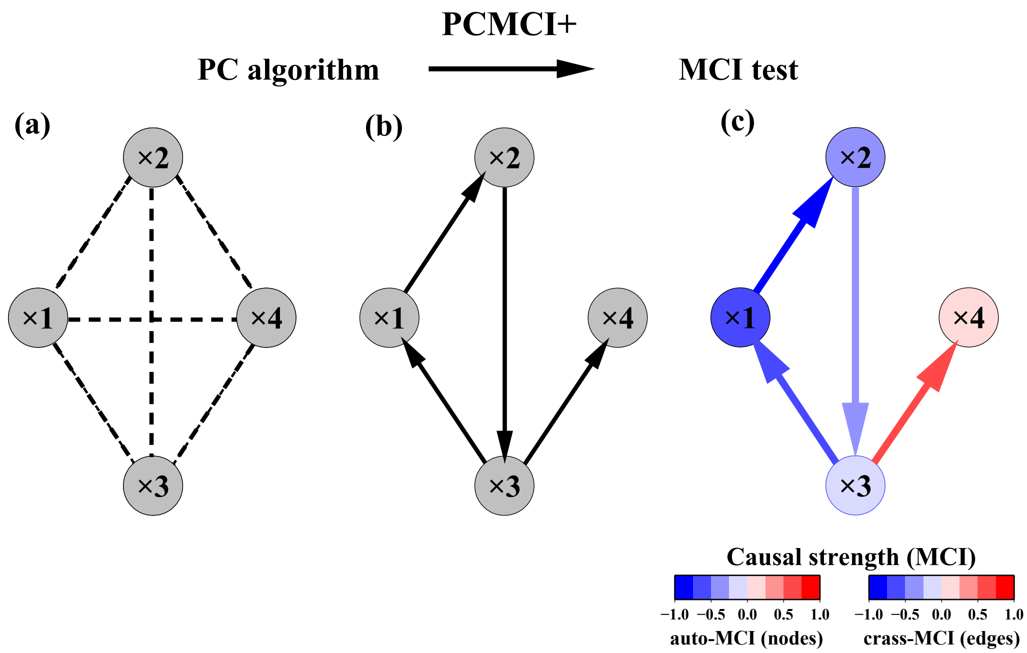
Causal discovery algorithm (PCMCI+)

We apply the Peter-Clark Momentary Conditional Independence Plus (PCMCI+) causal discovery algorithm to further analyze causal relationships between the runoff contributions of each sub-catchment and the primary hydrological components (precipitation P and potential evapotranspiration PET) of the Budyko curve[28,29,90]. Additionally, we investigate potential dependencies among streamflow series at upstream and downstream hydrological stations. The causal discovery algorithm does not violate the mass conservation principle ($Q = P - PET$)[29]. The PCMCI+ algorithm detects contemporaneous and lagged causal relationships in time series data through momentary conditional independence tests[91]. This method constructs a Directed Acyclic Graph (DAG) via a two-step process[92]: (1) a Markov set discovery algorithm (PC1) for conditional independence testing, and (2) the Momentary Conditional Independence (MCI) test for causal inference (Supplementary Fig. 8).

The PC1 algorithm initiates from a fully connected graph (Supplementary Fig. 8a). It progressively identifies conditional independence among variables by incrementally expanding the conditioning set and employing linear partial correlation tests[93,94]. This iterative process continues until it converges on a subset of fundamental links at a significance level of 0.05. The final output preserves only statistically significant causal relationships between variables (Supplementary Fig. 8b). Subsequently, building upon the estimated conditions identified by the PC1 algorithm, the second-stage MCI test assigns a partial correlation-based causal strength value (MCI) to each detected causal relationship (Supplementary Fig. 8c). The magnitude of the MCI quantifies the linkage intensity between variables[90,95]. The Python software for constructing a causal network is publicly available at https://tocsy.pik-potsdam.de/tigramite.php.

Ultimately, we conduct a comparative analysis to identify the key drivers behind runoff variations in each sub-catchment. Furthermore, we thoroughly investigate the interactive mechanisms between upstream and downstream watersheds under the combined influence of climate change and human activities.

Revised Supplementary Figures: Supplementary Fig. 8



Supplementary Fig. 8: Overview of the Peter-Clark Momentary Conditional Independence Plus (PCMCI+) causal discovery algorithm. The method consists of two main steps: the PC1 algorithm and MCI tests. PC1 begins with a fully connected graph as shown in **(a)**. It then iteratively eliminates links between variables by testing conditional independence with progressively increasing conditioning sets, as illustrated in **(b)**. Finally, the MCI tests employ the estimated conditions identified in the first step to infer causal relationships **(c)**. Node colors represent the auto-dependence degree of each component (auto-MCI), while link colors indicate the mutual dependence strength between variables (cross-MCI).

Revised Manuscript LL 258-311: Results section

Dominant drivers of changes in runoff

Based on the characteristics of climate change and human activities in different sub-catchments across various periods, we employ correlation analysis and PCMCI+ causal network analysis to identify the key driving factors behind river runoff changes within the basin. The correlation analysis reveals that the catchment's runoff contribution exhibits a highly significant positive correlation with precipitation ($P < 0.001$). In contrast, human disturbances' contribution to runoff shows a significant negative correlation with cultivated land area, construction land area, and reservoir/pond area (Fig. 7). Additionally, the area of permanent glaciers and snow cover is significantly negatively correlated with temperature and potential evapotranspiration, while being significantly positively correlated with runoff contribution. The correlation analysis indicates that precipitation, glacier melt, agricultural production, reservoir construction, and socio-economic development are significantly associated with runoff changes in the Yellow River Basin.

We further employ the PCMCI+ algorithm to assess the strength of causal relationships between runoff contribution in each sub-catchment and the main components of the Budyko water-energy balance (precipitation and potential evapotranspiration), as shown in Fig. 8 and Supplementary Fig. 18. The MCI test results demonstrate that sub-catchments at the headwaters of the mainstem (S1) or major tributaries (S5, S13-S15, and S19) display the strongest positive connections (highest MCI values: ranging from 0.46 to 0.77) between runoff contribution and precipitation. These same sub-catchments simultaneously show the strongest negative relationships (lowest MCI values: ranging from -0.49 to -0.19) with potential evapotranspiration. This indicates that precipitation and potential evapotranspiration are the dominant factors influencing runoff contribution in these sub-catchments. In contrast, in water-scarce regions with intensive human activities (S6-S12 and S20) and large reservoir-controlled areas (S2-S4 and S17-S18), the MCI values between runoff contribution and concurrent precipitation are either small or non-existent at the 0.05 significance level. Moreover, during Period II (1952-1986), when anthropogenic disturbances are stronger (Fig. 8b), the MCI values between runoff contribution and precipitation in the sub-catchments are lower than those in Period I (1987-2021) (Fig. 8c). This suggests that the influence of precipitation on runoff contribution in these catchments diminishes under human impacts, making anthropogenic interference a key driver of runoff changes. Additionally, significant causal links exist between runoff at upstream and downstream hydrological stations, with all MCI values being positive and relatively large (Fig. 8d-8f). This indicates mutual influences on runoff variations between upstream sub-catchments and downstream regions.

Ultimately, by integrating the relationships between runoff change contributions in each sub-catchment and climate change/human activities (Supplementary Tables 2-5), we identify distinct patterns. For the less disturbed headwater sub-catchment S1, the observed increase in runoff is primarily driven by ice and snow melt. However, subsequent reductions in glacial meltwater, coupled with intensified human activities, lead to a significant decrease in runoff during the change period compared to the reference period. In the middle and lower reaches experiencing stronger human interferences, reservoir storage emerges as the primary driver of runoff reduction in sub-catchments S2-S4 and S17-S18. Furthermore, reservoir operations in these areas induce significant seasonal flow fluctuations. Additionally, the "Grain for Green" project reduces agricultural irrigation water use in most sub-catchments. However, these water savings are offset by increasing socio-economic demands, resulting in minimal net gains or even negative changes in runoff contributions. In summary, the analysis demonstrates that runoff changes across the Yellow River Basin result from the combined effects of multiple factors. Key drivers include precipitation variability, declining glacial meltwater, reservoir construction, agricultural production, and socio-economic development.

Revised Manuscript LL 313-319: Results section.

Figure 9 illustrates the upstream-downstream interactions in runoff changes of major rivers under the influence of climate change and human activities. The causal relationship analysis between runoff at upstream and downstream hydrological stations further confirms mutual influences in runoff variations between upstream and downstream catchments. Moreover, the causal linkages between adjacent stations are stronger, while the strength of upstream-downstream causal relationships gradually weakens with increasing distance between stations (Fig. 8d-8f).

Revised Manuscript LL 328-352: Results section.

Additionally, we find that the causal strength of runoff volumes among hydrological stations during the change period (Fig. 8f) changes significantly compared to the reference period (Fig. 8e). Notably, the causal linkage strength between runoff at the downstream LJ station and upstream stations (from LZ to SZS in water-scarce regions) becomes even higher than that between closer stations (from TDG to LM). This suggests that water resource demands caused by human activities in downstream areas can influence runoff contributions from upstream sub-basins, thereby affecting runoff variations in upstream regions. This bottom-up feedback of human water demand specifically manifests as upstream sub-catchment areas (including even the water-scarce S5-S12 regions) increasing their contribution to runoff through human activities such as reducing local water usage (e.g., "Grain for Green") or enhancing local water supply (e.g., reducing surface areas of lakes, reservoirs, or glaciers). These measures collectively support downstream water resource needs for social development (Fig. 4 and Supplementary Fig. 9). Evidently, human water demand and the catchment's water storage capacity (reflected in underlying surface characteristics and water surface area changes, etc.) emerge as key drivers in realizing the process of upstream-downstream interaction. Notably, changes in basin water storage result from climatic changes and human activities in the preceding period and influence the runoff changes in the current or future periods. Furthermore, causal relationships between the runoff contribution quantities of the sub-watersheds and precipitation in lagged months exist at the 0.05 significance level. Some lagged-month causal linkage strengths (MCI) even exceed those of concurrent-month precipitation (Supplementary Fig. 18). This indicates that the impacts of climate change and human activities on runoff variation exhibit a lagged effect due to the water storage function of the catchment[36], such as the reduction in permanent glacier area affecting runoff variations.

Revised Figures: Fig. 8; and Revised Supplementary Figures: Supplementary Fig. 18

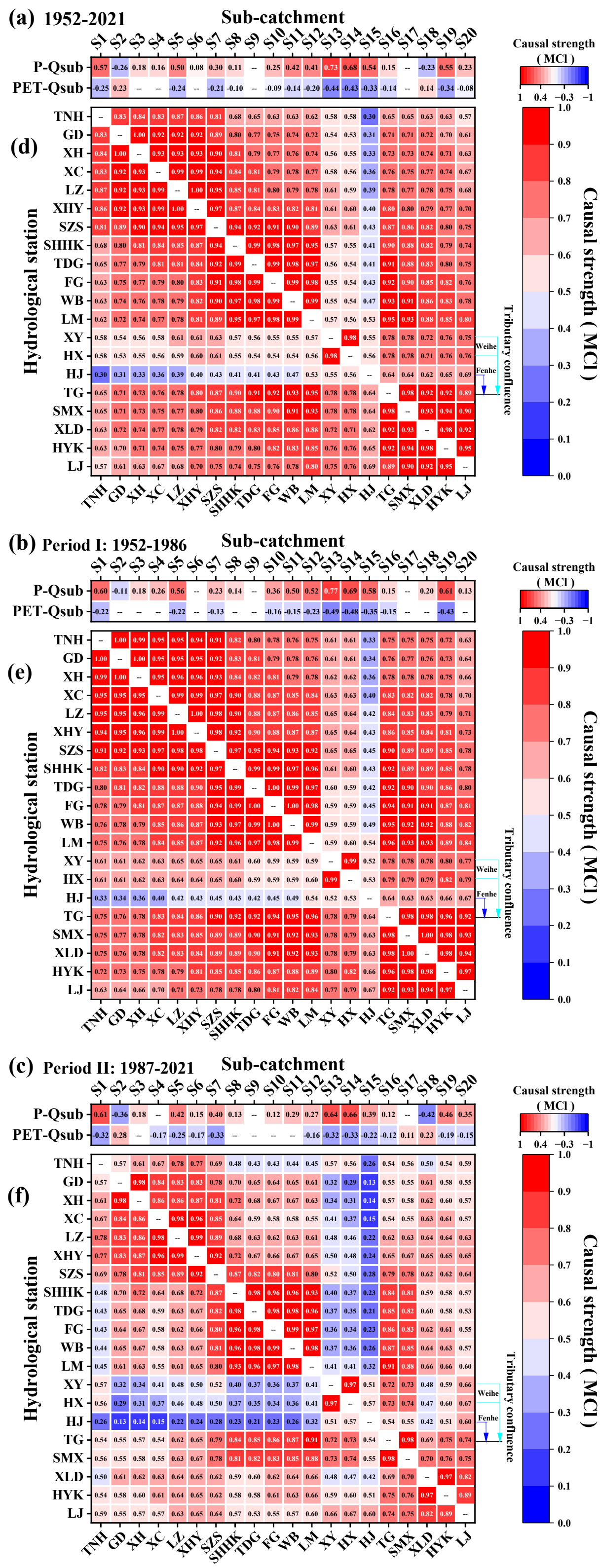
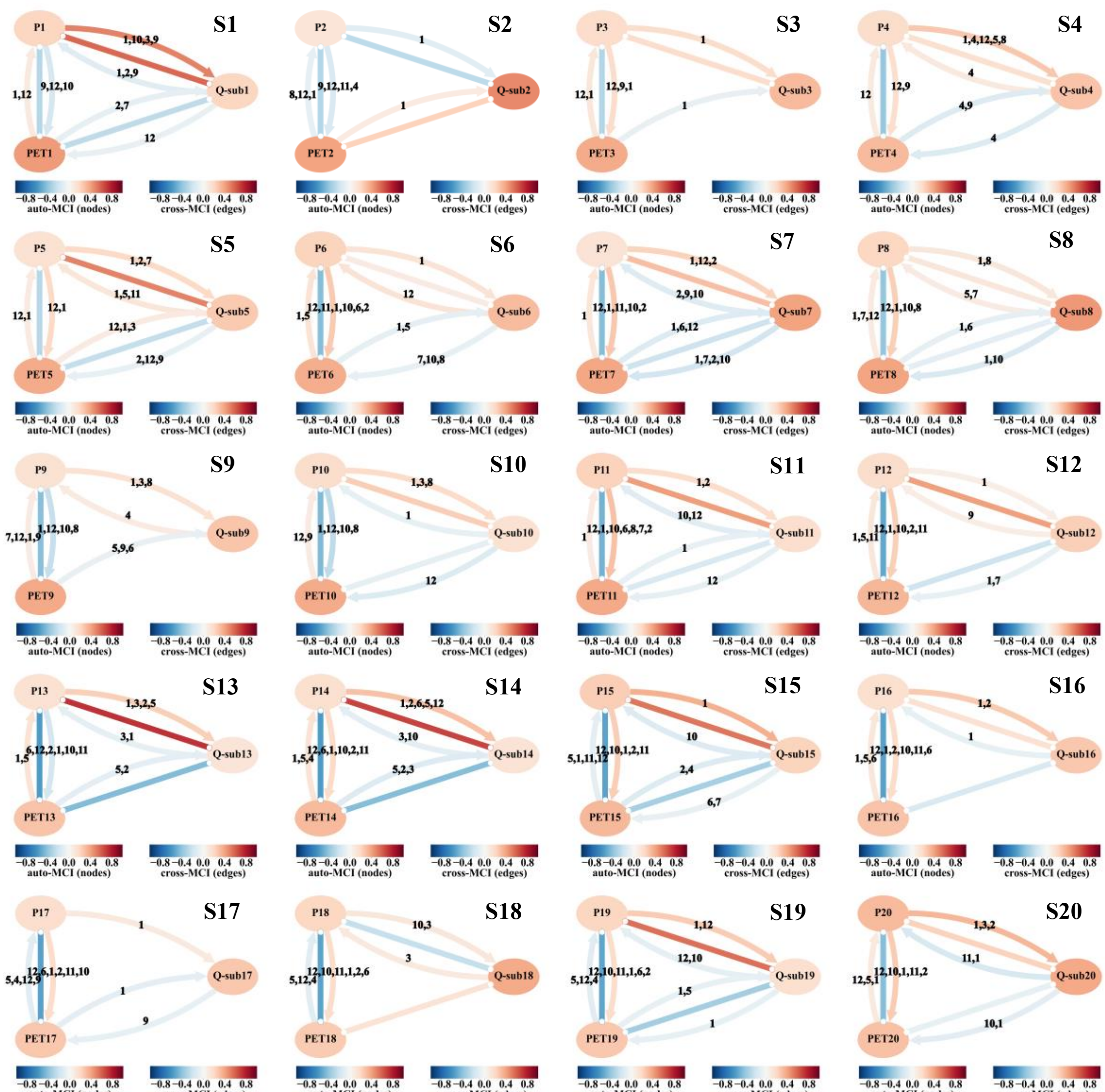


Fig. 8: Causal relationships derived from the PCMCI+ algorithm between runoff contributions and Budyko water-energy balance components (precipitation and potential

evapotranspiration) across sub-catchments, as well as between runoff at upstream and downstream hydrological stations.** Subfigures **(a)**, **(b)**, and **(c)** respectively present the MCI causal association strength between runoff contributions of each sub-catchment and contemporaneous precipitation/potential evapotranspiration during **(a)** 1952–2021, **(b)** 1952–1986, and **(c)** 1987–2021, with missing values indicating non-significant causal association at the 0.05 significance level; Subfigures **(d)**, **(e)**, and **(f)** show the MCI causal association strength between contemporaneous streamflows of upstream and downstream hydrological stations for the same three periods, respectively.



Supplementary Fig. 18: The significant causal network among monthly runoff contributions (Q_{sub}), precipitation (*P*), and potential evapotranspiration (*PET*) across sub-

catchments from 1952 to 2021, obtained through PCMCI+ analysis (significance level = 0.05, maximum time lag = 12 months). Node colors represent auto-correlation strength, while link edge colors indicate the (positive or negative) MCI coefficient strength between variables. Arrow direction and labels denote the causal relationship between time-lagged data of the source variable (with lag time in months indicated by link labels) and contemporaneous data of the target variable.

Revised Manuscript LL 359-370: Discussion section.

Our findings indicate that precipitation, reservoir construction, glacier and snowmelt, agricultural production, and socioeconomic development correlate significantly with changes in runoff contribution from upstream and downstream sub-catchments (Fig.7). Moreover, human activities have gradually dominated the impact on runoff, altering the causal relationship between precipitation and runoff (Fig.8a-c)[33,38,63,64]. The reduction in precipitation decreases the water resource allocation in the catchment area[22,30], while the intensification of anthropogenic disturbances and evapotranspiration exacerbates water loss[35,65]. These factors collectively reduce the runoff generation capacity of the catchment, leading to decreased streamflow at hydrological stations[49]. The impacts are particularly pronounced in downstream regions, where both climate change and human activities exert stronger influences[38,39,40].

Revised Manuscript LL 382-389: Discussion section.

Through the PCMCI+ causal analysis algorithm, we discover that a significant mutual causal relationship exists between upstream and downstream river runoff (Fig. 8d-f). Water-rich upstream catchments supply essential water resources to downstream water-scarce regions. This dependence has intensified with recent rapid downstream development, increasing both demand and reliance on upstream sources[38,39]. The impacts of climate change and human activities on runoff water resources in each sub-catchment accumulate and transmit through river connections, thereby leading to changes in downstream runoff[70].

Comment 5: Trend Analysis method needs clarification

There is a discrepancy between the main text and supplementary material. While the main text refers to linear regression, the supplementary section mentions the Mann-Kendall trend test. The authors should clarify which method was used where, and why. These methods differ in assumptions and sensitivities.

Response 5: Thank you for your helpful comments. The five methods introduced in the Supplementary Materials are change-point detection methods for long-term time series data, not trend analysis methods. We have explicitly clarified this distinction in the Supplementary Materials.

Furthermore, based on the results of the change point detection, we divided the long-term meteorological/hydrological data into multiple reference periods and change periods. By calculating the multi-year averages for each period, we have systematically examined the multi-year average change characteristics of these meteorological/hydrological elements.

The linear regression analysis method we adopted was primarily used to investigate the annual trend changes of meteorological and hydrological variables. All these methodological aspects have been properly clarified and revised in both the main text and Supplementary Materials.

Revised Supplementary LL 17-25: Supplementary Methods

Change point detection methods

We employ five widely used hydro-meteorological change point detection methods[1], including the Mann-Kendall change point detection, moving T-test change point detection, rank sum change point detection, cumulative anomaly and ordered clustering change point detection, to identify significant change points in climatic factors and hydrological station flows within each sub-catchment[2,3,4]. The purpose of using multiple change detection methods is to increase the confidence of the detection results. The specific steps of each change point detection method are as follows.

Revised Manuscript LL 535-552:

Since this study focuses on the impact of climatic variables on runoff and the interaction between upstream and downstream runoff changes, we uniformly select the most frequently occurring change point across the upstream and downstream runoff sequences to divide each watershed into a reference period (Period I: 1952-1986) and a change period (Period II: 1987-2021) (Supplementary Fig. 4). To minimize regional discrepancies in change points, we further conduct change point detection on the runoff data from each hydrological station during these two periods (Supplementary Fig. 5), resulting in four sub-periods: Period 1 (1952-1969), Period 2 (1970-1986); Period 3 (1987-2003), and Period 4 (2004-2021). Subsequently, we calculate the multi-year averages for each period to quantify the characteristics of variation in multi-year monthly/annual average meteorological and hydrological data within each sub-catchment before and after the change points.

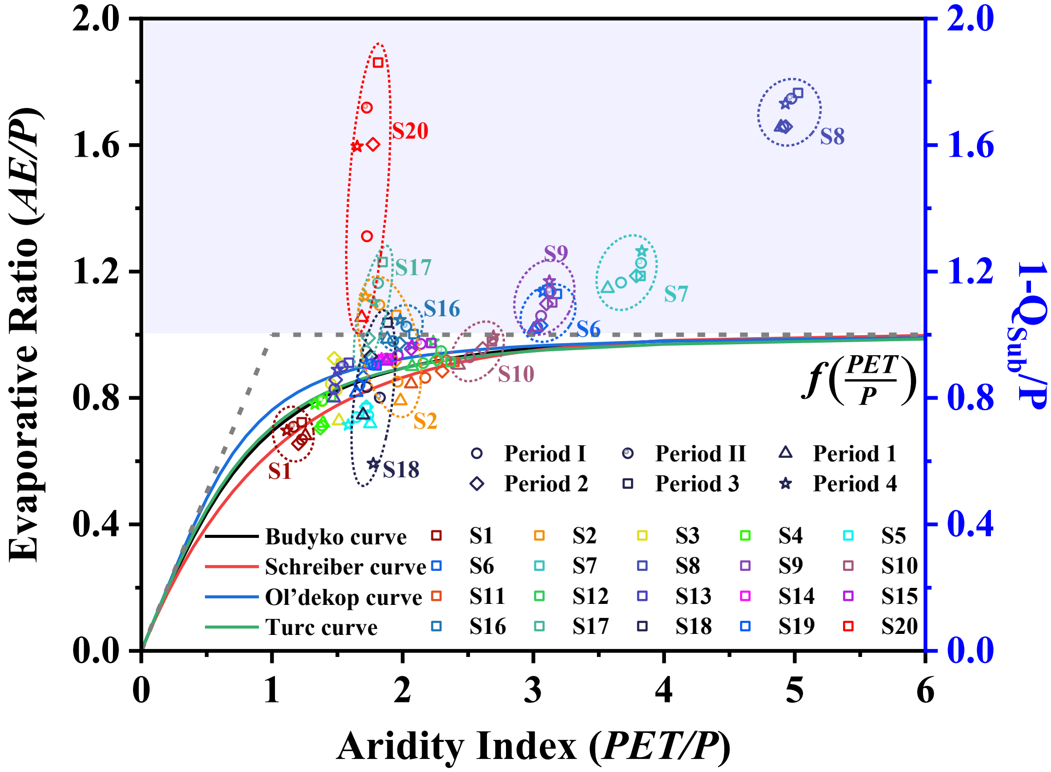
Furthermore, we combine linear regression analysis with the least squares method[83] to further investigate the temporal trends in annual average values of various meteorological and hydrological elements from 1952 to 2021. A trend is considered statistically significant if the slope of the fitting line is significantly different from zero (t-test: $P < 0.05$). Finally, we use hierarchical clustering analysis to explore the spatial distribution characteristics of climate change among different watersheds.

Comment 6: Use of multiple Budyko Curve types

The authors use four Budyko formulations, which is commendable. Including a visual comparison of observations over Budyko space would greatly improve transparency.

Response 6: We sincerely appreciate your constructive comments. We employe four Budyko curves to decompose the impacts of climate change and human activities on runoff variations, aiming to enhance the reliability of research findings.

Additionally, we have included a comparative diagram (Supplementary Fig. 7) displaying observational data from different periods within the Budyko space framework. This figure clearly illustrates the distribution of (PET/P, $1-Q_{Sub}/P$) for each sub-catchment during the change period relative to the reference period under the Budyko framework. This significantly improves the transparency of our research results by providing clear visual evidence of the hydrological relationships across all studied sub-basins.



Supplementary Fig. 7: The long-term mean annual runoff contribution and precipitation relationship data for each studied sub-catchment within the Budyko water-energy balance framework. Point shapes represent different periods, while colors denote different sub-catchments. Points within the light blue zone indicate sub-catchments with negative runoff contributions to the main river, representing either severe water scarcity or reservoir construction in these sub-catchments that utilize or store exogenous water resources from upstream areas.

Comment 7: Complexity of Period Division and Result Interpretation

The manuscript further subdivides the pre- and post-change periods into additional sub-periods, which complicates both the representation and interpretation of the results. The rationale for this additional division is not clearly justified. If possible, it would be more effective to present the results simply as "before" and "after" the detected change points. This would enhance the clarity of the findings and avoid overcomplicating the analysis without a strong conceptual justification for further periodization.

Response 7: Thank you for your comment. We consider it necessary to further subdivide Period

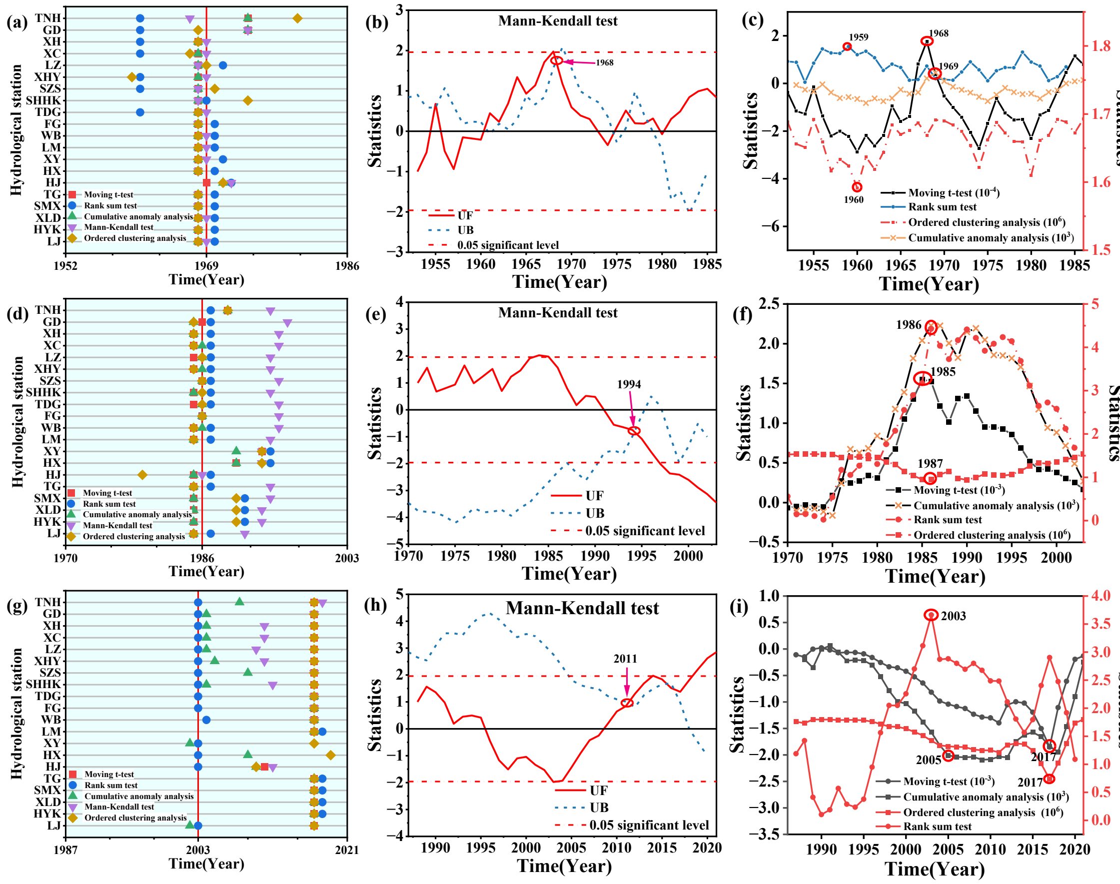
I and Period II for three key reasons. First, the 35-year time span is sufficiently long that it may obscure valuable hydrological information worthy of deeper investigation. Second, our change-point detection analysis for the 1952-2021 period revealed numerous change points occurring within both the 1952-1986 and 1987-2021 intervals, suggesting that climate change and human activities likely induced significant runoff changes during these sub-periods as well. Third, this additional temporal resolution provides essential data for the third-tier attribution analysis of runoff changes.

Consequently, we have conducted additional change-point detection analyses on runoff data for the three periods (1952-1986, 1970-2003, and 1987-2021). This provided a solid basis for further period segmentation.

Revised Manuscript LL 531-543:

To accurately analyze and quantify the variation patterns of climatic variables and river discharge, we initially employ five widely-used hydro-meteorological change point detection methods[17,19,62,74] to identify the significant change points in climatic factors and hydrological station flows within each sub-catchment (Supplementary Methods). Since this study focuses on the impact of climatic variables on runoff and the interaction between upstream and downstream runoff changes, we uniformly select the most frequently occurring change point across the upstream and downstream runoff sequences to divide each watershed into a reference period (Period I: 1952-1986) and a change period (Period II: 1987-2021) (Supplementary Fig. 4). To minimize regional discrepancies in change points, we further conduct change point detection on the runoff data from each hydrological station during these two periods (Supplementary Fig. 5), resulting in four sub-periods: Period 1 (1952-1969), Period 2 (1970-1986); Period 3 (1987-2003), and Period 4 (2004-2021).

Revised Supplementary Figures: Supplementary Fig. 5



Supplementary Fig. 5: The abrupt change points of the streamflow of each hydrological station across various periods. (a), **(d)**, and **(g)** display the streamflow change points detected during 1952-1986, 1970-2003, and 1987-2021 respectively, using the Mann-Kendall change point detection, moving t-test change point detection, rank-sum change point detection, cumulative anomaly, and ordered clustering methods. The point shapes and colors represent different change point detection methods. **(b)**, **(e)**, and **(h)** illustrate examples of streamflow change point detection at XHY station using the Mann-Kendall method for 1952-1986, 1970-2003, and 1987-2021 periods respectively. Similarly, **(c)**, **(f)**, and **(i)** present the corresponding results obtained from the moving t-test change point detection, rank-sum change point detection, cumulative anomaly, and ordered clustering methods for these three periods at XHY station.

Comment 8: Writing and Structural Clarifications

o Line 59–60: *The phrase "have shifted upstream" is ambiguous—does this refer to seasonal shifts or geographic redistribution? Please clarify.*

o Line 61: *Suggest revising as: "An increasing trend may lead to greater reliance on …"*
o Line 73: *The sentence appears incomplete. Please revise for clarity.*
Response 8: Thank you for your comments. In the initially submitted manuscript, the phrase "have shifted upstream" in Lines 59-60 referred to geographical redistribution, which has been clarified in the revised version. The sentence originally appearing at Line 61 has been comprehensively revised. Similarly, the statement at Line 73 has been substantially improved and refined. The specific modifications are presented as follows:
Revised Manuscript LL 59-61: Recent studies have shown that the river flow distribution across approximately 29% of the global terrestrial surface has significantly shifted from downstream to upstream regions, exacerbating water scarcity in 7.4%-16.5% of downstream areas[38,39].
Revised Manuscript LL 61-63: An increasing trend may lead to greater reliance on upstream "water tower" runoff by nearly half of the world's downstream areas[40].
Revised Manuscript LL 74-77: Given the observations in recent years of many iconic rivers that were once perennial becoming intermittent[43,44], it is imperative to conduct an in-depth attribution analysis of runoff changes in large river basins[45], particularly for the Yellow River, the world's fifth-largest river[46].

*#### **Minor Comments***
Comment 9:
• ***Line 51, 56, 74, and 556:*** *The following recent studies are highly relevant and should be cited when discussing human impacts on the water cycle and Budyko-based attribution:*
o *Zaerpour et al. (2025) on agriculture and water-energy balance.*
o *Hatami et al. (2024) on seasonal runoff variability and anthropogenic factors.*
o *Liu et al. (2021) on spatial runoff changes and Budyko partitioning.*
• ***Equation References:*** *All equations should be accompanied by references or derivations to guide the reader and justify their inclusion.*
References
• Wang, D., & Hejazi, M. (2011). Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. Water Resources Research, 47(10).

• Zaerpour, M., Hatami, S., Ballarin, A. S., Knoben, W. J., Papalexiou, S. M., Pietroniro, A., & Clark, M. P. (2024). Impacts of agriculture and snow dynamics on catchment water balance in the US and Great Britain. Communications Earth & Environment, 5(1), 733.

• Zaerpour, M., Hatami, S., Ballarin, A. S., Papalexiou, S. M., Pietroniro, A., & Nazemi, A. (2025). Agriculture's impact on water–energy balance varies across climates. Proceedings of the National Academy of Sciences, 122(12), e2410521122.

Response 9: We sincerely appreciate your comments and references. We have cited the highly relevant references at the corresponding locations in Lines 51, 56, 74, and 556, as well as in other sections. By incorporating methodologies from these publications, we have significantly enhanced the quality of this research paper. Furthermore, in the Methods section, all equations have been properly cited.

Revised Manuscript LL 43-55: Consequently, numerous studies have decomposed and quantified the relative contributions of climate change and human activities to river runoff variations across different periods based on abrupt streamflow changes[16,17,18,19]. Among these, the Budyko water-energy balance curve approach[20,21,22], with its distinct physical significance, has been widely applied in attribution analysis of runoff variations in basins with precipitation gradients of 35-2,980 mm and drainage areas of 1-6 million square kilometers[23,24]. Furthermore, scholars have explored the impacts of land-surface modifications, glacial melt, and agricultural irrigation on runoff by analyzing deviations from the Budyko curve in representative catchments[25,26,27], combined with the Peter-Clark MCI Plus (PCMCI+) causal discovery algorithm[28,29,30]. Most of these studies focused on the contribution of regional or overall annual runoff changes in individual unit catchment areas[31,32,33,34], and a small number addressed seasonal runoff trends[35,36,37].

Revised Manuscript LL 595-597: Methodology section

$$\frac{AE'}{P} = f(\varphi) = \begin{cases} (1 - e^{-\varphi}) & \text{Schreiber}^{85} \\ \varphi \times tanh(1/\varphi) & \text{Ol'dekop}^{86} \\ \sqrt{\varphi \times (1 - e^{-\varphi}) \times tanh(1/\varphi)} & \text{Budyko}^{84} \\ \left(1/\sqrt{1 + \varphi^{-2}}\right) & \text{Turc}^{87} \end{cases} \tag{3}$$

where AE'/P is the theoretical evapotranspiration ratio on the Budyko curve corresponding to the aridity index. φ is the simple drought index, i.e., (PET/P).

Revised Manuscript LL 819-827; 867-869; 983-989; 997-1012: References section

28. Zaerpour, M. et al. Impacts of agriculture and snow dynamics on catchment water balance in the U.S. and Great Britain. *Communications Earth & Environment* **5**, doi:10.1038/s43247-024-01891-w (2024).
29. Zaerpour, M., Hatami, S., Ballarin, A. S., Papalexiou, S. M., Pietroniro, A., & Nazemi, A. Agriculture's impact on water–energy balance varies across climates. *P Natl Acad Sci USA*, **122**(12) e2410521122 (2025).
30. Liu, J. & You, Y. The roles of catchment characteristics in precipitation partitioning within the Budyko framework. *Journal of Geophysical Research: Atmospheres* **126**, doi:10.1029/2021jd035168 (2021).
45. Wang, D. & Hejazi, M. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research* **47**, doi:10.1029/2010wr010283 (2011).
84. Budyko, M. I. *Climate and Life*, Vol **508** (Academic, 1974).
85. Schreiber, P. U¨ ber die Beziehungen zwischen dem Niederschlag und der Wasserfu¨ hrung der Flu¨ ße in Mitteleuropa. *Z. Meteorol*. **21** (10), 441–452 (1904).
86. Ol'dekop, E.M. On evaporation from the surface of river basins in Russia. *Trans Meteorol Obs Univ Tartu 4 Univ Tartu*, Tartu (1911).
87. Turc, L. Le bilan d'eau des sols: relations entre les précipitations, l'évaporation et l'écoulement. *Ann Agron* **5**, 491–569 (1953).
90. Runge, J., Nowack, P., Kretschmer, M., Flaxman, S. & Sejdinovic, D. Detecting and quantifying causal associations in large nonlinear time series datasets. *Sci. Adv.* **5**, eaau4996 (2019).
91. Delforge, D., de Viron, O., Vanclooster, M., Van Camp, M. & Watlet, A. Detecting hydrological connectivity using causal inference from time series: synthetic and real karstic case studies. *Hydrol. Earth Syst. Sci.* **26**, 2181–2199 (2022).
92. Runge, J. et al. Inferring causation from time series in earth system sciences. *Nat. Commun.* **10**, 2553 (2019).
93. Runge, J. et al. Identifying causal gateways and mediators in complex spatio-temporal systems. *Nature Communications* **6**, doi:10.1038/ncomms9502 (2015).
94. Runge, J. Discovering contemporaneous and lagged causal relations in autocorrelated nonlinear time series datasets. In *Proc. 36th Conference on Uncertainty in Artificial Intelligence (UAI)* (eds Peters, J. & Sontag, D.) vol. 124, 1388–1397 (PMLR, 2020).

95. Spirtes, P. & Glymour, C. An algorithm for fast recovery of sparse causal graphs. *Soc. Sci. Comput. Rev.* **9**, 62–72 (1991). **and so on**).

Revised Supplementary LL 17-25: Supplementary Methods

Change point detection methods

We employ five widely used hydro-meteorological change point detection methods[1], including the Mann-Kendall change point detection, moving T-test change point detection, rank sum change point detection, cumulative anomaly and ordered clustering change point detection, to identify significant change points in climatic factors and hydrological station flows within each sub-catchment[2,3,4]. The purpose of using multiple change detection methods is to increase the confidence of the detection results. The specific steps of each change point detection method are as follows.

Revised Supplementary LL 268-281: Supplementary References:

1. Xie, P., Gu, H., Sang, Y. F., Wu, Z. & Singh, V. P. Comparison of different methods for detecting change points in hydroclimatic time series. *Journal of Hydrology* **577**, doi:10.1016/j.jhydrol.2019.123973 (2019).
2. Dey, P. & Mishra, A. Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions. *Journal of Hydrology* **548**, 278-290, doi:10.1016/j.jhydrol.2017.03.014 (2017).
3. Luan, J. et al. Evaluating the uncertainty of eight approaches for separating the impacts of climate change and human activities on streamflow. *Journal of Hydrology* **601**, doi:10.1016/j.jhydrol.2021.126605 (2021).
4. Wang, W., Zhang, Y. & Tang, Q. Impact assessment of climate change and human activities on streamflow signatures in the Yellow River Basin using the Budyko hypothesis and derived differential equation. *Journal of Hydrology* **591**, doi:10.1016/j.jhydrol.2020.125460 (2020).

Responses to Reviewer #2

The contributions of climate change and human interferences to runoff variation and their spatiotemporal differences have been examined in multiple independent unit catchment areas; however, comprehensive investigation into the interaction relationships between upstream and *downstream sub-catchment areas is lacking. Here, we propose a new three-tiered framework for attributing runoff variation to investigate the spatiotemporal patterns, driving factors, and interaction mechanisms between upstream and downstream under climate change and human activities over a 70-year period (1952-2021) in the Yellow River Basin. This topic is interesting and within the scope of Communications Earth and Environment.*

Response: We are deeply grateful for the time you have taken to review our manuscript and for your insightful comments. Based on your valuable comments, we have carefully revised and improved the manuscript. Specifically, we have made detailed modifications and refinements to the following sections:

(1) We have thoroughly revised and enhanced the content of the abstract, incorporating statistical results.

(2) In the Introduction and Methods sections, we have expanded the discussion on research progress related to assessing the impacts of climate change and human activities on runoff variations. Furthermore, we have improved the framework for attributing runoff changes.

(3) We have supplemented the description of runoff data sources and acquisition methods.

(4) In the Results and Discussion sections, we have further strengthened the comparative analysis of the evolution characteristics of hydrology, climate and human activities among the upstream and downstream sub-catchments.

(5) We have further delved into the physical mechanisms underlying runoff changes in this study. Furthermore, we have elucidated the interaction mechanisms and key driving factors between upstream and downstream sub-catchments.

Finally, we have improved the overall writing throughout the manuscript. Below, we present detailed revisions along with our point-by-point responses to your comments.

Comment 1: *the Abstract, I would recommend providing more statistical results.*

Response 1: We appreciate your comments on the abstract section of our manuscript. We have thoroughly revised and refined the abstract. In this updated version, we have incorporated more critical statistical results.

Revised Manuscript LL 12-26:

Abstract: The contributions of climate change and human activities to runoff variation have been examined in multiple individual catchments, but upstream-downstream interaction relationships remain underexplored. Here, we propose a three-tiered attribution framework to investigate the spatiotemporal patterns, underlying drivers, and upstream-downstream relationships of runoff variations in the Yellow River Basin (1952-2021). The results indicate that the longitudinal cumulative effects of climatic (ranging from -8.6% upstream to 7.1% downstream relative to the whole basin) and anthropogenic disturbance (15.2%-92.9%) factors lead to higher risks of runoff variations in downstream regions, with more significant seasonal fluctuations (particularly in reservoir-regulated reaches). Glaciers, lakes, and reservoirs' storage capacities cause lagged effects of climate change and human activities on runoff variations, while simultaneously serving as critical drivers for inter-basin water resource regulation. Integrating comprehensive understanding of multi-scale hydrological variability drivers and spatial interaction mechanisms is essential for advancing adaptive river basin management and sustainable water resources allocation.

Comment 2: *The Budyko has been widely used in attributing and detecting human/climate changes in hydrological cycle. The advancement of this paper should be discussed.*

Response 2: We are grateful for your constructive comments. In the introduction and method sections, we have added a discussion on the research progress of the runoff change attribution analysis methods. Additionally, due to the significant regional heterogeneity of large research areas, we propose a three-tier runoff change attribution analysis framework suitable for large basins. The attribution analysis method in this study has made certain advancements based on previous research, as follows:

(1) From the perspective of the assessment method that quantifies the impact of climate change and human activities on runoff changes in each sub-catchment:

We improved upon the Budyko curve decomposition method. **On one hand**, we define the human activity contribution to runoff change during the change period compared to the reference period as: the difference between the [Vertical deviation of Point B (change period) from the Budyko curve] and the [Vertical deviation of Point A (reference period) from the Budyko curve] (Supplementary Fig. 6c). This will reduce the error that may arise from the fact that the position of point A in the reference period (PET/P, $1-Q_{Sub}/P$) does not lie on the Budyko curve. Additionally, to enhance comparability across sub-catchments, we apply the same non-parametric Budyko curve equation to all sub-catchments. We also employ multiple non-parametric Budyko curve equations to ensure the robustness of our results.

On the other hand, for water-scarce midstream and downstream sub-catchments that rely on upstream inflows, we assume that under the long-term multi-year average conditions, the evapotranspiration losses of the upstream external water resources caused by climate change can be disregarded. This is because, if humans do not directly extract water from the river channel, the loss of runoff resources caused solely by evapotranspiration from the water surface as the flow passes through these sub-catchments is relatively small. Therefore, this portion of runoff loss from upstream inflow can be entirely attributed to the direct impact of human activities on runoff changes.

Thus, the loss of upstream inflows is an additional contribution of human activities to runoff changes, which are distinct from the evapotranspiration losses induced by human activities within the sub-catchment itself. Consequently, this portion of upstream inflow loss should not be directly included in the calculation of actual evapotranspiration within the Budyko framework. This is analogous to how estimating actual evapotranspiration in a local catchment requires prior exclusion of cross-regional water resource influences. After deducting this upstream inflow loss, and under the assumption of long-term multi-year averages, changes in sub-catchment soil water storage remain negligible. The actual evapotranspiration point B’ in these sub-catchments still adheres to the assumptions of Budyko’s water-energy balance theory. The Budyko curve decomposition method used in this study remains applicable to these sub-catchments, with the key distinction being that the runoff contribution point B in the Budyko framework no longer approximates the actual evapotranspiration point B’. Therefore, the shift in the aridity index-evaporation ratio relationship from point C to point B still reflects the influence of human activities on runoff changes. However, the actual evapotranspiration point B’ serves as an intermediate variable that cancels out when calculating the total contribution of human activities to runoff changes.

Indubitably, the non-parametric Budyko curve decomposition method employed herein has limitations. For example, non-parametric Budyko curves overlook the impact of differences in underlying surface characteristics across sub-catchments on the attribution of runoff variations. However, it provides insights into the interplay of runoff changes among upstream and downstream sub-catchments under combined climate change and human activity pressures. The justification, reasonableness, and limitations of the Budyko water-energy balance curve decomposition approach are revised in the Methods and Discussion sections.

(2) From the perspective of the comprehensive three-tier attribution analysis framework for runoff changes constructed in this study:

This study divided the entire large-scale river basin into multiple sub-catchments connected by the mainstem, aiming to evaluate the impacts of climate change and human activities on runoff variations. This partitioning approach enables:

- **Holistic analysis** of climate change and human activity contributions to runoff changes across the entire basin;
- **Regional-scale examination** of spatiotemporal differences in climate change, human activities, and runoff characteristics among sub-catchments;
- **Identification of key climatic and anthropogenic drivers** triggering significant runoff changes in the basin;
- **In-depth exploration** of interaction mechanisms in runoff changes between upstream and downstream sub-catchments under climate change and human disturbances.

Previous studies have predominantly focused on the attribution analysis of runoff changes in individual catchments. However, few studies have investigated the interaction mechanisms and critical driving factors among interconnected upstream and downstream sub-catchments under combined climate change and human activities.

Furthermore, we introduced the PCMCI+ causal discovery algorithm to better disentangle the effects of climatic and anthropogenic factors on runoff variations, as well as to identify the key driving factors. The specific modifications are detailed as follows:

Revised Manuscript LL 42-58: Introduction section

The variability of river flow is a crucial “indicator” for monitoring the potential impacts of climatic and anthropogenic factors on water resources[15]. Consequently, numerous studies have decomposed and quantified the relative contributions of climate change and human activities to river runoff variations across different periods based on abrupt streamflow changes[16,17,18,19]. Among these, the Budyko water-energy balance curve approach[20,21,22], with its distinct physical significance, has been widely applied in attribution analysis of runoff variations in basins with precipitation gradients of 35-2,980 mm and drainage areas of 1-6 million square kilometers[23,24]. Furthermore, scholars have explored the impacts of land-surface modifications, glacial melt, and agricultural irrigation on runoff by analyzing deviations from the Budyko curve in representative catchments[25,26,27], combined with the Peter-Clark MCI Plus (PCMCI+) causal discovery algorithm[28,29,30]. Most of these studies focused on the contribution of regional or overall annual runoff changes in individual unit catchment areas[31,32,33,34], and a small number addressed seasonal runoff trends[35,36,37]. However, none of these studies have compared the relative contributions and driving mechanisms of climate change and human interference to upstream and downstream runoff variations among different catchment areas within a basin.

Revised Manuscript LL 574-679:

Decompose the contributions of climate change and human activities

Budyko demonstrates that the evaporation ratio (AE/P) of a basin is primarily governed by the ratio of potential evapotranspiration (PET) to precipitation (P), which is denoted as the aridity index ($\varphi = PET/P$). He further proposes corresponding water-energy balance curve equations for basins[84]. However, other factors, such as vegetation, soil water storage, and rainfall seasonality, affect precipitation partitioning, resulting in scattered observations around the Budyko curve[28,30]. Consequently, researchers have proposed various forms of water-energy balance equations tailored to different watershed characteristics[17,19,20]. Furthermore, deviations between specific catchments and the Budyko curve have been used to evaluate the impact of basin attributes[28,29]. The broad applicability of Budyko water-energy balance framework has been extensively validated[19,42]. Building on this, we employ the detection of change points combined with the water-energy coupling equation to quantitatively assess the contribution of climate change and human activities to runoff variation in each sub-catchment. Given the significant anthropogenic influences and regional heterogeneity among sub-catchments, changes in evapotranspiration due to altered basin properties may be closely linked to human activities[42,53]. We therefore apply four non-parametric Budyko curves (Equation 3) to compare upstream and downstream sub-catchments. These non-parametric curves exhibit strong robustness in eliminating uncertainties associated with parameterization and capturing complex hydrological responses across heterogeneous watersheds[28,29].

$$\frac{AE'}{P} = f(\varphi) = \begin{cases} (1 - e^{-\varphi}) & \text{Schreiber}^{85} \\ \varphi \times tanh(1/\varphi) & \text{Ol'dekop}^{86} \\ \sqrt{\varphi \times (1 - e^{-\varphi}) \times tanh(1/\varphi)} & \text{Budyko}^{84} \\ \left(1/\sqrt{1 + \varphi^{-2}}\right) & \text{Turc}^{87} \end{cases} \quad (3)$$

where AE'/P is the theoretical evapotranspiration ratio on the Budyko curve corresponding to the aridity index. φ is the simple drought index, i.e., (PET/P).

In this study, we employ a decomposition method to separate the impacts of climate change and human activities on runoff variation[17,30,45], as illustrated in Supplementary Fig. 6a. In this study, the impact of human activities on runoff excludes indirect effects induced by anthropogenic climate change[45]. Specifically, we hypothesize that combined human activities and climate change shift the relationship between aridity index and evaporation ratio in the catchment from Point A (PET_1/P_1, AE_1/P_1) in the reference period to Point B (PET_2/P_2, AE_2/P_2) in the changed period. Under the sole influence of climate change, the aridity index-evaporation ratio relationship would follow the Budyko curve, transitioning from Point A to Point C (PET_2/P_2, AE_2'/P_2), which shares the same aridity index as Point B. Direct human activities then drive the relationship from Point C to Point B. This reveals that climate change affects both horizontal and vertical components of runoff variation in the catchment, while direct human activities only induce vertical changes in runoff[30,45]. Under long-term average conditions, where soil water storage variations are negligible[17], runoff can be expressed as a function of precipitation and the evaporation ratio:

$$Q_{Sub} = P(1 - AE/P) \quad (4)$$

Consequently, the contribution of human activities to runoff variation can be calculated as follows:

$$\Delta Q_h = P_2(AE_2'/P_2 - AE_2/P_2) \quad (5)$$

For a given region, differences in multi-year average streamflow (ΔQ_{Sub}) between the change period (Q_2) and reference period (Q_1) at hydrological stations result from the combined effects of climate change (ΔQ_c) and human activities (ΔQ_h):

$$\Delta Q_{Sub} = Q_2 - Q_1 = \Delta Q_c + \Delta Q_h \quad (6)$$

Consequently, the impacts of climate change on runoff variation can be expressed as follows:

$$\Delta Q_c = \Delta Q_{Sub} - \Delta Q_h \quad (7)$$

However, the focus of this study is to analyze the changes in runoff during the change period compared to the reference period, where the catchment area in the reference period is not in a pristine natural state. Therefore, many studies have reconstructed the Budyko curve equation based on the physical characteristics of the reference period catchment (Supplementary Fig. 6b), which may be a good practice for investigating the variations of individual catchments over different periods[19,21,25]. However, this study emphasizes the analysis of the interconnectedness between upstream and downstream catchments. Developing Budyko curve equations for each catchment would introduce greater uncertainties into subsequent analyses while compromising the comparability across catchments [19]. Consequently, this study adopts non-parametric curve equations to decompose the impacts of climate change and human activities on runoff variations. Additionally, multiple non-parametric water-energy balance curve equations are employed to ensure the reliability of the results.

In addition, the runoff during the reference period is also affected by anthropogenic disturbances[18,88,89], as shown in Supplementary Fig. 6c. Therefore, it is necessary to subtract the deviation between the reference period and the Budyko curve to reduce the discrepancies in anthropogenic impacts on runoff variation across different catchments[22]. Furthermore, the mid-to-downstream catchments in this study receive and utilize upstream external water resources. Under the assumption of long-term multi-year average conditions, the water loss through climatic evaporation or evapotranspiration from these external resources and reservoir regulation is negligible[20]. This portion of water represents an additional contribution to runoff changes due to human activities, distinct from the evapotranspiration losses caused by human activities[17]. Consequently, after subtracting this water volume, the actual evapotranspiration Point B' in these catchments still adheres to the assumptions of the Budyko water-energy balance theory. The Budyko curve and decomposition method employed in this study remain applicable to these catchments. Thus, the shift in the relationship between aridity index and evaporation ratio from Point C to Point B still reflects the impact of human activities on runoff variation. The actual evapotranspiration Point B' serves as an intermediate variable that cancels out when calculating the total contribution of human activities to runoff changes. Therefore, the upstream inflow recharge and reservoir regulation may cause the relationship between the drought index and evaporation ratio in the sub-catchment to deviate from the water supply control line of the Budyko framework, entering the blue-shaded region beyond this boundary (as shown in Supplementary Fig. 6d and Supplementary Fig. 7, where $1 - Q_{Sub}/P > 1$).

Therefore, based on the decomposition method illustrated in Supplementary Fig. 6c, the formula for calculating the direct contribution of human activities to catchment runoff variation during the change period can be derived as follows:

$$\Delta Q_h = P_2(AE'_2/P_2 - Q_2/P_2) - P_1(AE'_1/P_1 - Q_1/P_1) \quad (8)$$

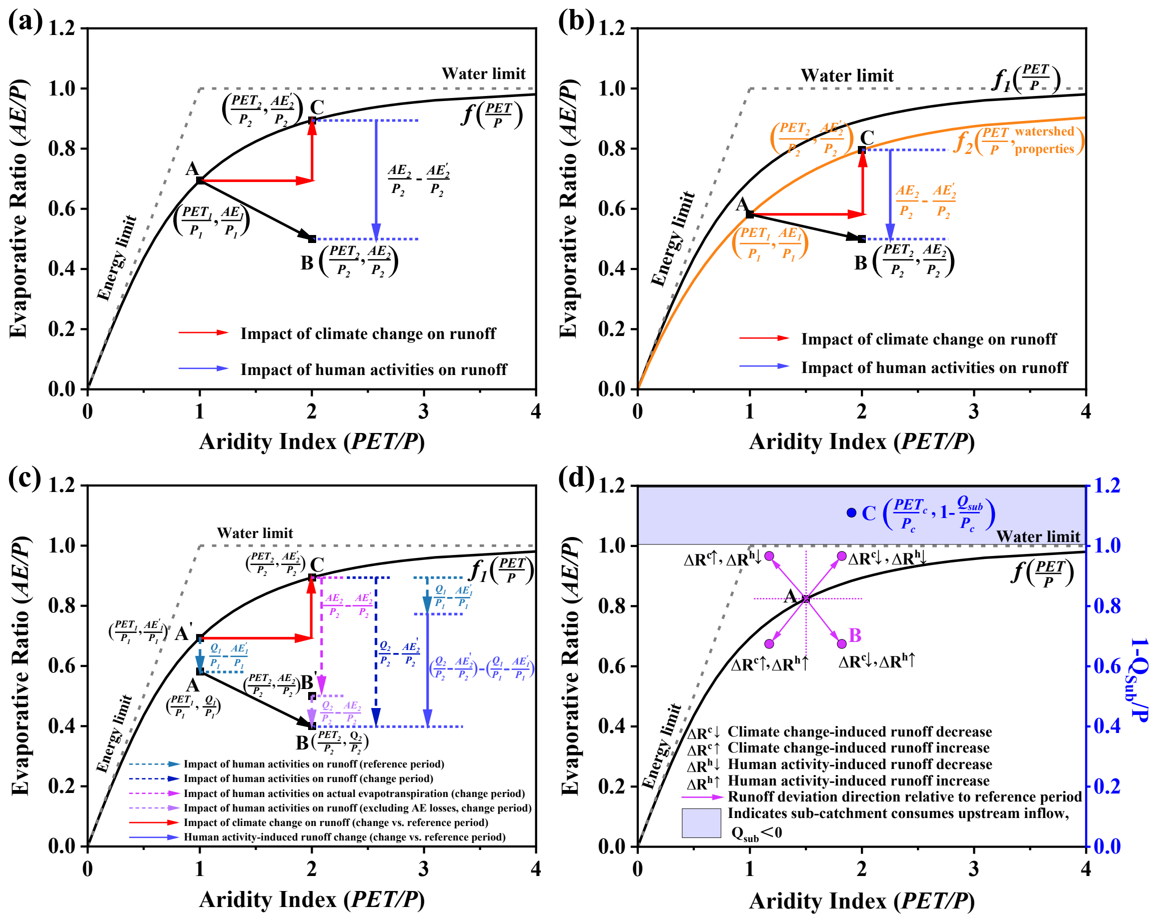
where Q_1 and Q_2 respectively represent the multi-year averages of the runoff contributions from each sub-catchment during the reference period and change period. AE_1'/P_1 and AE_2'/P_2 respectively represent the theoretical evapotranspiration ratios corresponding to the aridity index for the reference period and the change period. Similarly, the contribution of climate change in the change period relative to the reference period to the runoff variation in the catchment area can be derived from Equation (7). Then, the contribution rates of climate change and human activities to the variation in runoff of the sub-catchment can be calculated using the following formula:

$$\omega_h = \frac{\Delta Q_h}{|\Delta Q_{Sub}|} \times 100\% \quad (9)$$

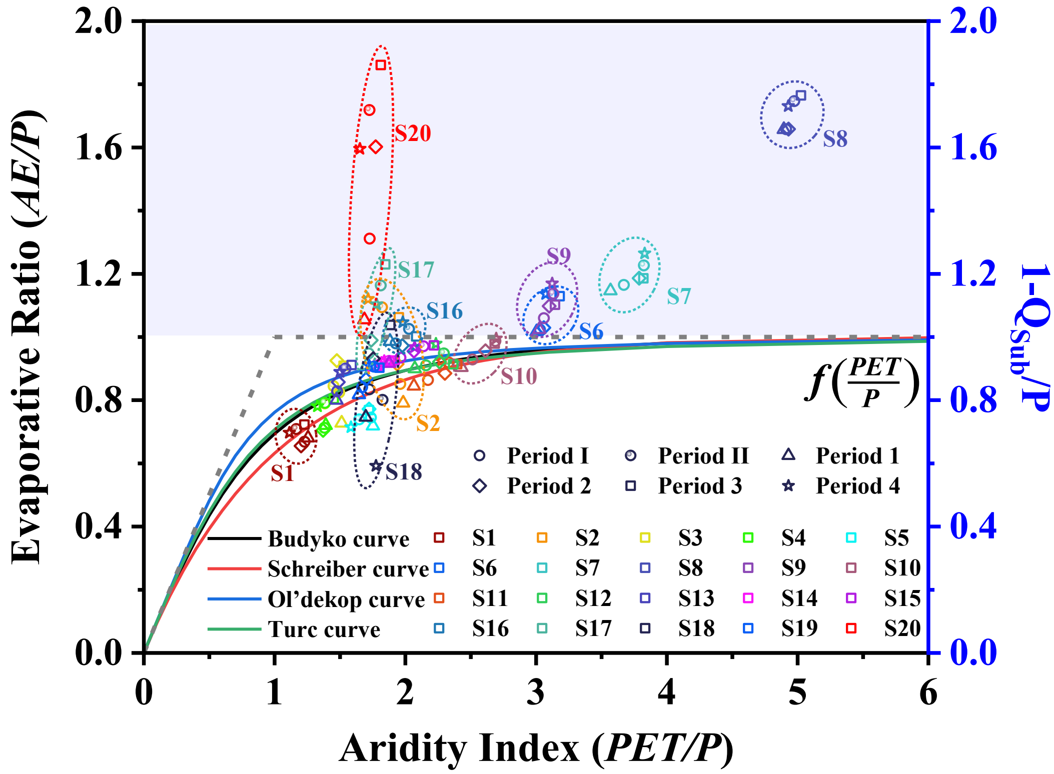
$$\omega_c = \frac{\Delta Q_c}{|\Delta Q_{Sub}|} \times 100\% \quad (10)$$

where ω_c and ω_h are the percentage of the change in runoff contribution caused by climate change and human activities to the total change in runoff contribution of the sub-catchment, respectively; $\omega_c > 0$ ($\omega_h > 0$) indicates a positive contribution from climate change (human activities), increasing the runoff contribution of the watershed[30,45]. Otherwise, it is a negative contribution, as shown in Supplementary Fig. 6d.

Revised Supplementary Figures: Supplementary Fig. 6-7 and Supplementary Fig. 3



Supplementary Fig. 6: Overview of methods for decomposing the Budyko water-energy balance curve to quantify the impacts of climate change and human activities on runoff variation. **(a)** Traditional non-parametric Budyko curve decomposition method; **(b)** Parametric water-energy balance curve decomposition method; **(c)** The non-parametric Budyko curve decomposition method comparing change periods to reference periods in this study, which incorporates the impact of external water resource contributions (excluding evapotranspiration losses caused by human activities) on runoff changes; **(d)** Characteristics of climate change and human activity impacts on runoff coefficient ($R = Q_{Sub}/P$), with anomalous zones (light blue areas) showing long-term runoff contribution amounts and precipitation relationships in midstream/downstream sub-catchments receiving external water resources.



Supplementary Fig. 7: The long-term mean annual runoff contribution and precipitation relationship data for each studied sub-catchment within the Budyko water-energy balance framework. Point shapes represent different periods, while colors denote different sub-catchments. Points within the light blue zone indicate sub-catchments with negative runoff contributions to the main river, representing either severe water scarcity or reservoir construction in these sub-catchments that utilize or store exogenous water resources from upstream areas.

Revised Manuscript LL 692-725: Methodology section

In this study, we evaluate the correlation between the runoff contribution of each sub-catchment and various climatic and human interference factors using the Spearman correlation[33] in OriginPro 2024 software:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \tag{11}$$

where ρ represents the Spearman correlation coefficient, d_i represents the difference in ranks for each pair of variables, and n is the sample size.

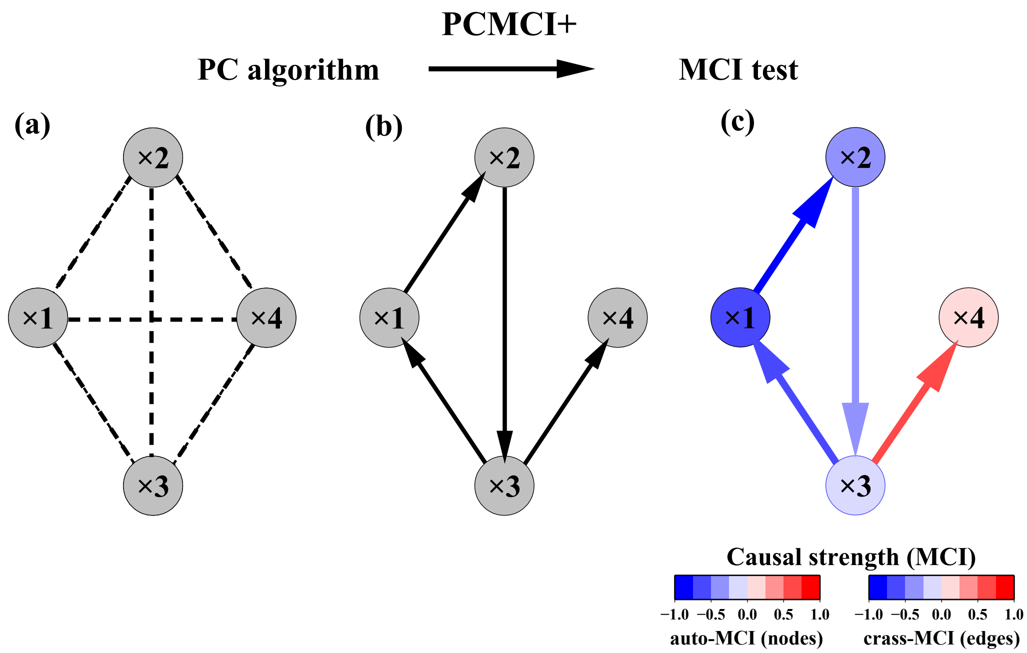
Causal discovery algorithm (PCMCI+)

We apply the Peter-Clark Momentary Conditional Independence Plus (PCMCI+) causal discovery algorithm to further analyze causal relationships between the runoff contributions of each sub-catchment and the primary hydrological components (precipitation P and potential evapotranspiration PET) of the Budyko curve[28,29,90]. Additionally, we investigate potential dependencies among streamflow series at upstream and downstream hydrological stations. The causal discovery algorithm does not violate the mass conservation principle ($Q = P - PET$)[29]. The PCMCI+ algorithm detects contemporaneous and lagged causal relationships in time series data through momentary conditional independence tests[91]. This method constructs a Directed Acyclic Graph (DAG) via a two-step process[92]: (1) a Markov set discovery algorithm (PC1) for conditional independence testing, and (2) the Momentary Conditional Independence (MCI) test for causal inference (Supplementary Fig. 8).

The PC1 algorithm initiates from a fully connected graph (Supplementary Fig. 8a). It progressively identifies conditional independence among variables by incrementally expanding the conditioning set and employing linear partial correlation tests[93,94]. This iterative process continues until converging on a subset of fundamental links at a significance level of 0.05. The final output preserves only statistically significant causal relationships between variables (Supplementary Fig. 8b). Subsequently, building upon the estimated conditions identified by the PC1 algorithm, the second-stage MCI test assigns a partial correlation-based causal strength value (MCI) to each detected causal relationship (Supplementary Fig. 8c). The magnitude of the MCI quantifies the linkage intensity between variables[90,95]. The Python software for constructing a causal network is publicly available at https://tocsy.pik-potsdam.de/tigramite.php.

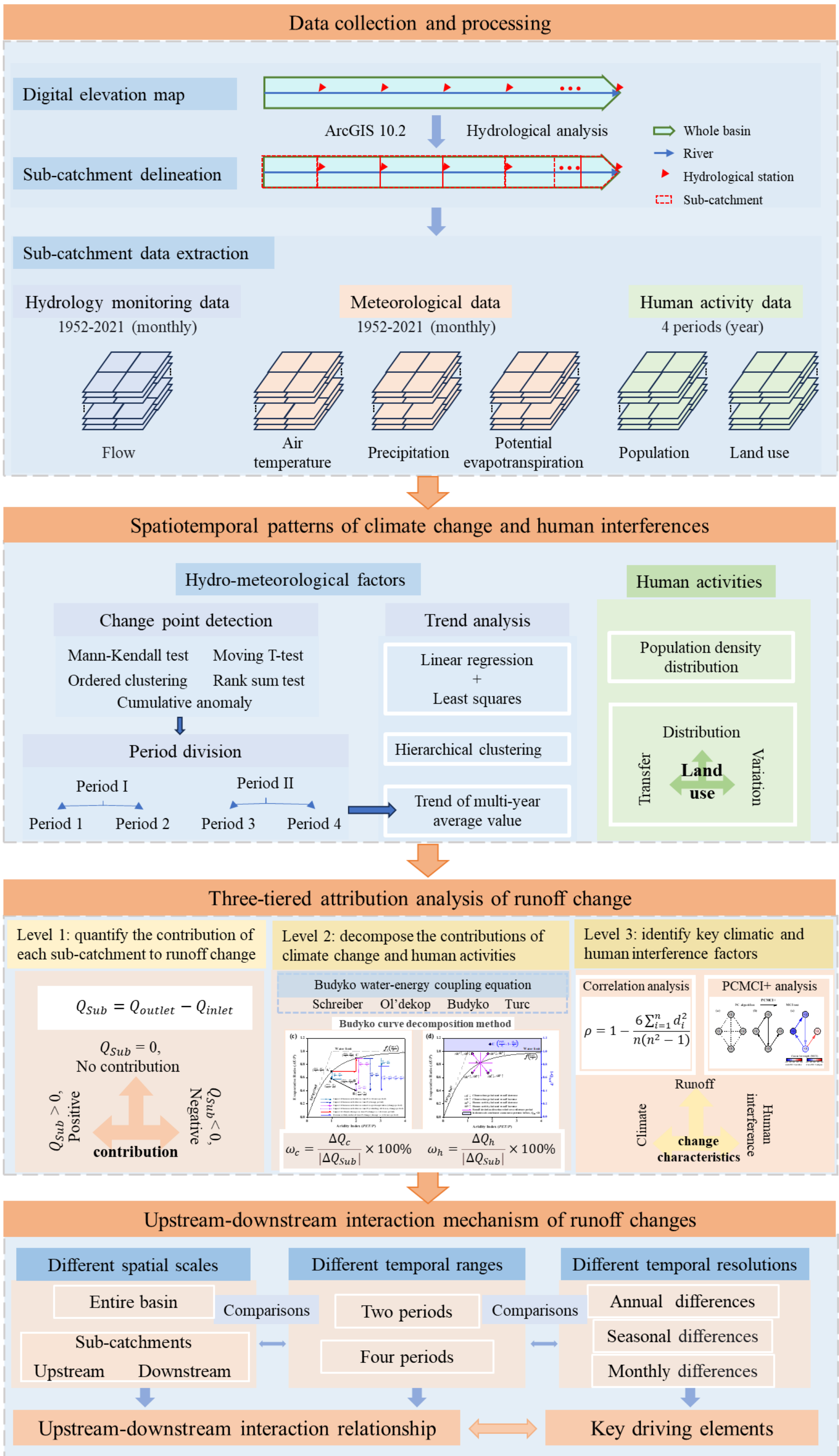
Ultimately, we conduct a comparative analysis to identify the key drivers behind runoff variations in each sub-catchment. Furthermore, we thoroughly investigate the interactive mechanisms between upstream and downstream watersheds under the combined influence of climate change and human activities.

Revised Supplementary Figures: Supplementary Fig. 8



Supplementary Fig. 8: Overview of the Peter-Clark Momentary Conditional Independence Plus (PCMCI+) causal discovery algorithm. The method consists of two main steps: the PC1 algorithm and MCI tests. PC1 begins with a fully connected graph as shown in **(a)**. It then iteratively eliminates links between variables by testing conditional independence with progressively increasing conditioning sets, as illustrated in **(b)**. Finally, the MCI tests employ the estimated conditions identified in the first step to infer causal relationships **(c)**. Node colors represent the auto-dependence degree of each component (auto-MCI), while link colors indicate the mutual dependence strength between variables (cross-MCI).

Revised Supplementary Figures: Supplementary Fig. 3



Supplementary Fig. 3: The overall framework of the research process and the three-tiered attribution analysis method for streamflow variation.

Comment 3: *The streamflow data is difficult to collect in China. Could you provide more details about the open access way to access to these series?*

Response 3: Thank you for your comments. We have revised and expanded the methodology for obtaining runoff data from hydrological stations across the entire basin. Recent hydrological data of the Yellow River Basin can be acquired from the official website of the Yellow River Conservancy Commission (YRCC). We have provided the corresponding web address. However, early-period hydrological data are currently unavailable through open-access channels. Therefore, the historical hydrological data used in this study were primarily provided by the Hydrology Bureau of the Yellow River Conservancy Commission. Additionally, the selection of hydrological data for this research was based on the completeness of records available from various hydrological stations across the Yellow River Basin.

Revised Manuscript LL 499-503: Additionally, we obtain monthly runoff data (1952-2021) for 20 hydrological stations from the Hydrology Bureau of the Yellow River Conservancy Commission (http://www.yrcc.gov.cn/) and its published "Yellow River Hydrology Yearbook". These stations comprise 17 along the Yellow River main channel, 2 on the Weihe River, and 1 on the Fenhe River.

Revised Manuscript LL 734-736: Monthly runoff data are collected from the Hydrology Bureau of the Yellow River Conservancy Commission (http://www.yrcc.gov.cn/) and its published "Yellow River Hydrology Yearbook".

Comment 4: *It is widely reported that upstream and downstream usually have different evolution pattern. More discussion is necessary.*

Response 4: We sincerely appreciate your comments. In the revised version of our manuscript, we have substantially revised both the Results and Discussion sections. Notably, we have enhanced the discussion on evolutionary patterns of watershed characteristics, including climate change, human activities, and runoff variations across upstream and downstream sub-catchments. Additionally, this study has:

- Investigated the differential contributions of upstream and downstream sub-catchments to the overall runoff changes within the entire basin;
- Quantified the respective impacts of climate change and human activities on runoff variations in

each sub-catchment;

- Identified key climatic and anthropogenic drivers triggering runoff alterations in each sub-catchment;
- Unraveled the interaction mechanisms between upstream and downstream sub-catchments.

It is important to highlight that our Results section presents extensive comparative analyses of watershed evolution characteristics between upstream and downstream regions. In the Discussion section, we particularly focus on sub-catchments that exhibit significant spatial heterogeneity in their evolutionary patterns between upstream and downstream areas.

Revised Manuscript LL 272-311: Results section

We further employ the PCMCI+ algorithm to assess the strength of causal relationships between runoff contribution in each sub-catchment and the main components of the Budyko water-energy balance (precipitation and potential evapotranspiration), as shown in Fig. 8 and Supplementary Fig. 18. The MCI test results demonstrate that sub-catchments at the headwaters of the mainstem (S1) or major tributaries (S5, S13-S15, and S19) display the strongest positive connections (highest MCI values: ranging from 0.46 to 0.77) between runoff contribution and precipitation. These same sub-catchments simultaneously show the strongest negative relationships (lowest MCI values: ranging from -0.49 to -0.19) with potential evapotranspiration. This indicates that precipitation and potential evapotranspiration are the dominant factors influencing runoff contribution in these sub-catchments. In contrast, in water-scarce regions with intensive human activities (S6-S12 and S20) and large reservoir-controlled areas (S2-S4 and S17-S18), the MCI values between runoff contribution and concurrent precipitation are either small or non-existent at the 0.05 significance level. Moreover, during Period II (1952-1986), when anthropogenic disturbances are stronger (Fig. 8b), the MCI values between runoff contribution and precipitation in the sub-catchments are lower than those in Period I (1987-2021) (Fig. 8c). This suggests that the influence of precipitation on runoff contribution in these catchments diminishes under human impacts, making anthropogenic interference a key driver of runoff changes. Additionally, significant causal links exist between runoff at upstream and downstream hydrological stations, with all MCI values being positive and relatively large (Fig. 8d-8f). This indicates mutual influences on runoff variations between upstream sub-catchments and downstream regions.

Ultimately, by integrating the relationships between runoff change contributions in each sub-catchment and climate change/human activities (Supplementary Tables 2-5), we identify distinct patterns. For the less disturbed headwater sub-catchment S1, the observed increase in runoff is primarily driven by ice and snow melt. However, subsequent reductions in glacial meltwater, coupled with intensified human activities, lead to a significant decrease in runoff during the change period compared to the reference period. In the middle and lower reaches experiencing stronger human interferences, reservoir storage emerges as the primary driver of runoff reduction in sub-catchments S2-S4 and S17-S18. Furthermore, reservoir operations in these areas induce significant seasonal flow fluctuations. Additionally, the "Grain for Green" project reduces agricultural irrigation water use in most sub-catchments. However, these water savings are offset by increasing socio-economic demands, resulting in minimal net gains or even negative changes in runoff contributions. In summary, the analysis demonstrates that runoff changes across the Yellow River Basin result from the combined effects of multiple factors. Key drivers include precipitation variability, declining glacial meltwater, reservoir construction, agricultural production, and socio-economic development.

Revised Manuscript LL 359-381: Discussion section

Our findings indicate that precipitation, reservoir construction, glacier and snowmelt, agricultural production, and socioeconomic development correlate significantly with changes in runoff contribution from upstream and downstream sub-catchments (Fig.7). Moreover, human activities have gradually dominated the impact on runoff, altering the causal relationship between precipitation and runoff (Fig.8a-c)[33,38,63,64]. The reduction in precipitation decreases the water resource allocation in the catchment area[22,30], while the intensification of anthropogenic disturbances and evapotranspiration exacerbates water loss[35,65]. These factors collectively reduce the runoff generation capacity of the catchment, leading to decreased streamflow at hydrological stations[49]. The impacts are particularly pronounced in downstream regions, where both climate change and human activities exert stronger influences[38,39,40]. As is well known, sufficient water resources remain an important factor supporting societal development, which also explains why downstream regions with wider catchment areas develop faster economically and socially than upstream regions[38]. However, with the enhancement of climate change and human activities throughout the entire basin, the runoff contribution from each sub-watershed decreases. The cumulative effects of these drivers along the upstream and downstream catchments amplify runoff variation risks in downstream river reaches, directly impacting the socio-economic development of these areas[66,67]. Therefore, over the past decade or so, the basin has implemented a series of proactive measures[14], such as the "Grain for Green" policy[55,68], to mitigate the negative impacts of water scarcity. However, the effectiveness remains limited under the combined influence of climate change and rapid socio-economic development[69].

Revised Manuscript LL 406-428: Discussion section

The three-tiered runoff change attribution analysis framework we construct compares the evolutionary characteristics of climate change and human activities across different spatial scales (entire basin vs. sub-basins), temporal scopes (two vs. four change periods), and temporal resolutions (annual vs. monthly) alongside their impacts on runoff variation. This multi-dimensional analysis reveals more hidden information about runoff variation drivers[35]. For instance, in the source region S1, climate warming during the reference period leads to glacier melt, thereby increasing early runoff; however, as meltwater diminishes, streamflow declines significantly despite increased precipitation during the change period[5,72]. The primary anthropogenic factors influencing runoff in sub-catchments S2-S4 and S17-S18 are reservoir construction and operation, while the remaining mid-lower sub-catchments are mainly associated with agricultural activities and socio-economic development. From 2004 to 2021 (P4), increased precipitation in nearly all sub-basins partially relieves basin-wide water scarcity pressures. However, 50% of sub-catchments still show negative runoff contributions relative to the reference period (P3), reflecting heightened human influence on runoff (Fig. 6). Notably, the severely water-stressed sub-catchment S20 experiences positive human-induced impacts on runoff changes during this period, likely due to arable land shifts and the influence of the South-to-North Water Diversion Project[73]. Additionally, significant seasonal differences in the impact of climate change and human activities on river runoff exist, particularly in reservoir-regulated sections[26,38]. These conclusions hold significant theoretical and practical importance for formulating adaptive strategies to climate change and evaluating the effectiveness of water resource management policies.

Comment 5: *This study identified dominant factors of changes in runoff. However, some physical mechanisms are lacking.*

Response 5: Thank you for your comments. In the resubmitted manuscript, we have comprehensively revised and improved the relevant discussions in the Results and Discussion sections. Specifically, we have examined the impact mechanisms of climate change and human activities on runoff variations within each sub-catchment. Additionally, we have placed particular emphasis on discussing the interaction mechanisms between upstream and downstream sub-catchments under the combined influences of climate change and human activities.

The overall research framework of this study consists of:

- Through trend analysis, we identify that hydrological stations in the lower Yellow River mainstem and its major tributaries face higher risks of runoff variation.
- We establish a three-level attribution analysis framework to reveal the underlying causes, physical mechanisms, and key driving factors of runoff changes.
- The entire basin is divided into multiple river-connected sub-catchments.
- We conduct comparative analyses of hydro-meteorological characteristics, human activity patterns, and runoff contribution changes between upstream and downstream sub-catchments across different time periods.
- Using the physically-based Budyko curve decomposition method, we quantify the contributions of climate change and human activities to runoff variations in each sub-catchment.
- Correlation analysis and PCMCI+ causal discovery methods are employed to identify key climatic and anthropogenic disturbance factors affecting runoff changes in individual sub-catchments and the entire watershed.

Based on the above analyses, we have revealed the underlying physical mechanisms of runoff changes induced by both climatic and anthropogenic factors, as well as the interaction mechanisms between upstream and downstream sub-catchments. In this study, we have primarily identified the following physical mechanisms:

First, we identify the physical mechanisms underlying the reduced runoff contributions. The primary mechanisms are: decreased precipitation reduces the total allocable water resources within the basin, while increased evapotranspiration and intensified human activities exacerbate water losses, collectively leading to diminished runoff generation capacity across all sub-catchments. Additionally, in downstream catchment areas, the impact of climate change and human activities on runoff variations is more pronounced. Meanwhile, anthropogenic influences have gradually become the dominant factor.

Second, we reveal the lagged response mechanisms of runoff variations to climate change and human activities. Natural and artificial water storage features, including permanent glaciers, snowpack, lakes and reservoirs, play crucial roles in these processes through their water storage and release functions. For instance, climate warming accelerates glacial melting, initially increasing runoff in early periods. However, substantial reductions in glacier area subsequently diminish meltwater contributions, leading to significantly decreased runoff compared to earlier stages.

Furthermore, we identified spatially interactive mechanisms of runoff changes between upstream and downstream sub-catchments under climate change and human influences. These include: (1) the cumulative effect from upstream to downstream, and (2) the water demand feedback mechanism from downstream to upstream. The upstream-downstream cumulative effect results in downstream areas facing greater runoff variation risks under intensifying climate change and human activities. Meanwhile, due to the increasing water demand in downstream water-scarce regions, a feedback mechanism of water resource requirements from downstream to upstream has been formed. This demands that upstream regions either reduce their water consumption or increase the runoff contribution from catchment areas to meet the needs of human activities in downstream regions. This process will impact the runoff volume in both upstream and downstream river channels. Additionally, the water storage capacity of glaciers, lakes, and reservoirs within the basin is a critical factor in the interactions between these sub-catchments. Furthermore, the water storage capacity of the catchment area is key to achieving rational water resource allocation between upstream and downstream regions.

Revised Manuscript LL 312-352:

Upstream-downstream interaction mechanism of runoff changes

Figure 9 illustrates the upstream-downstream interactions in runoff changes of major rivers under the influence of climate change and human activities. The causal relationship analysis between runoff at upstream and downstream hydrological stations further confirms mutual influences in runoff variations between upstream and downstream catchments. Moreover, the causal linkages between adjacent stations are stronger, while the strength of upstream-downstream causal relationships gradually weakens with increasing distance between stations (Fig. 8d-8f). Intuitively, the changes in downstream river flow are the cumulative sum of contributions from all upstream sub-catchments, potentially even reflecting the combined effects of climatic changes and human activities within each of these upper basins (Fig. 6). This indicates that climate change and human activities in the upper catchment exert an influence on the variation of river runoff downstream, encompassing all reaches below the catchment point. Notably, the cumulative effect means that when both climate change and human activities in these upper sub-catchments contribute uniformly (positive or negative), downstream areas may face a higher risk of runoff fluctuations.

Additionally, we find that the causal strength of runoff volumes among hydrological stations during the change period (Fig. 8f) changes significantly compared to the reference period (Fig. 8e). Notably, the causal linkage strength between runoff at the downstream LJ station and upstream stations (from LZ to SZS in water-scarce regions) becomes even higher than that between closer stations (from TDG to LM). This suggests that water resource demands caused by human activities in downstream areas can influence runoff contributions from upstream sub-basins, thereby affecting runoff variations in upstream regions. This bottom-up feedback of human water demand specifically manifests as upstream sub-catchment areas (including even the water-scarce S5-S12 regions) increasing their contribution to runoff through human activities such as reducing local water usage (e.g., “Grain for Green”) or enhancing local water supply (e.g., reducing surface areas of lakes, reservoirs, or glaciers). These measures collectively support downstream water resource needs for social development (Fig. 4 and Supplementary Fig. 9). Evidently, human water demand and the catchment’s water storage capacity (reflected in underlying surface characteristics and water surface area changes, etc.) emerge as key drivers in realizing the process of upstream-downstream interaction. Notably, changes in basin water storage result from climatic changes and human activities in the preceding period and influence the runoff changes in the current or future periods. Furthermore, causal relationships between the runoff contribution quantities of the sub-watersheds and precipitation in lagged months exist at the 0.05 significance level. Some lagged-month causal linkage strengths (MCI) even exceed those of concurrent-month precipitation (Supplementary Fig. 18). This indicates that the impacts of climate change and human activities on runoff variation exhibit a lagged effect due to the water storage function of the catchment[36], such as the reduction in permanent glacier area affecting runoff variations.

Revised Manuscript LL 359-381:

Our findings indicate that precipitation, reservoir construction, glacier and snowmelt, agricultural production, and socioeconomic development correlate significantly with changes in runoff contribution from upstream and downstream sub-catchments (Fig.7). Moreover, human activities have gradually dominated the impact on runoff, altering the causal relationship between precipitation and runoff (Fig.8a-c)[33,38,63,64]. The reduction in precipitation decreases the water resource allocation in the catchment area[22,30], while the intensification of anthropogenic disturbances and evapotranspiration exacerbates water loss[35,65]. These factors collectively reduce the runoff generation capacity of the catchment, leading to decreased streamflow at hydrological stations[49]. The impacts are particularly pronounced in downstream regions, where both climate change and human activities exert stronger influences[38,39,40]. As is well known, sufficient water resources remain an important factor supporting societal development, which also explains why downstream regions with wider catchment areas develop faster economically and socially than upstream regions[38]. However, with the enhancement of climate change and human activities throughout the entire basin, the runoff contribution from each sub-watershed decreases. The cumulative effects of these drivers along the upstream and downstream catchments amplify runoff variation risks in downstream river reaches, directly impacting the socio-economic development of these areas[66,67]. Therefore, over the past decade or so, the basin has implemented a series of proactive measures[14], such as the "Grain for Green" policy[55,68], to mitigate the negative impacts of water scarcity. However, the effectiveness remains limited under the combined influence of climate change and rapid socio-economic development[69].

Revised Manuscript LL 382-405:

Through the PCMCI+ causal analysis algorithm, we discover that a significant mutual causal relationship exists between upstream and downstream river runoff (Fig. 8d-f). Water-rich upstream catchments supply essential water resources to downstream water-scarce regions. This dependence has intensified with recent rapid downstream development, increasing both demand and reliance on upstream sources[38,39]. The impacts of climate change and human activities on runoff water resources in each sub-catchment accumulate and transmit through river connections, thereby leading to changes in downstream runoff[70]. Simultaneously, downstream areas can also feedback their water resource demands to upstream areas[43]. In response, the upstream areas can influence the variation in river runoff from downstream to upstream by altering human activities or utilizing reserved water resources (reduction in water body area). Although we do not quantitatively separate the contributions of catchment storage variable changes to runoff, the variations in water body area, such as glaciers, lakes, and reservoirs, indicate that storage variables play a significant role in runoff changes[21]. Additionally, the water storage function of the watershed (change in water surface area) leads to a lag effect in the impact of climate change and human activities on runoff variation[36]. Therefore, expanding regional water storage (reservoir construction) and strengthening water resource management can address the increasingly severe extreme climate events and the uneven spatial and temporal distribution of water resources[14]. In summary, our study emphasizes the causal relationship between climate change/human activities and runoff variation, as well as the interconnected nature of runoff changes and water scarcity between upstream and downstream regions (Fig. 9). This may help provide references for promoting cross-regional water resource regulation and mitigating the occurrence of water resource conflict events[71].

Revised Figures: Fig. 8-9;

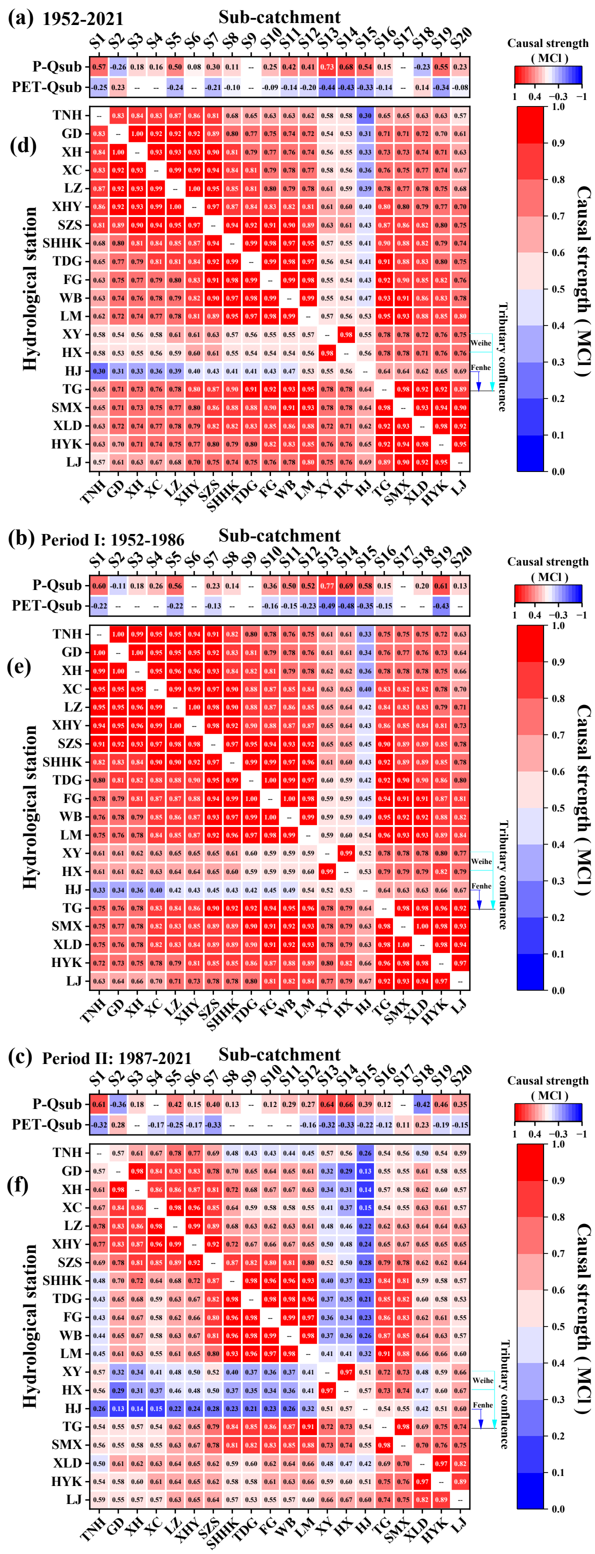


Fig. 8: Causal relationships derived from the PCMCI+ algorithm between runoff contributions and Budyko water-energy balance components (precipitation and potential evapotranspiration) across sub-catchments, as well as between runoff at upstream and

downstream hydrological stations. Subfigures **(a)**, **(b)**, and **(c)** respectively present the MCI causal association strength between runoff contributions of each sub-catchment and contemporaneous precipitation/potential evapotranspiration during **(a)** 1952–2021, **(b)** 1952–1986, and **(c)** 1987–2021, with missing values indicating non-significant causal association at the 0.05 significance level; Subfigures **(d)**, **(e)**, and **(f)** show the MCI causal association strength between contemporaneous streamflows of upstream and downstream hydrological stations for the same three periods, respectively.

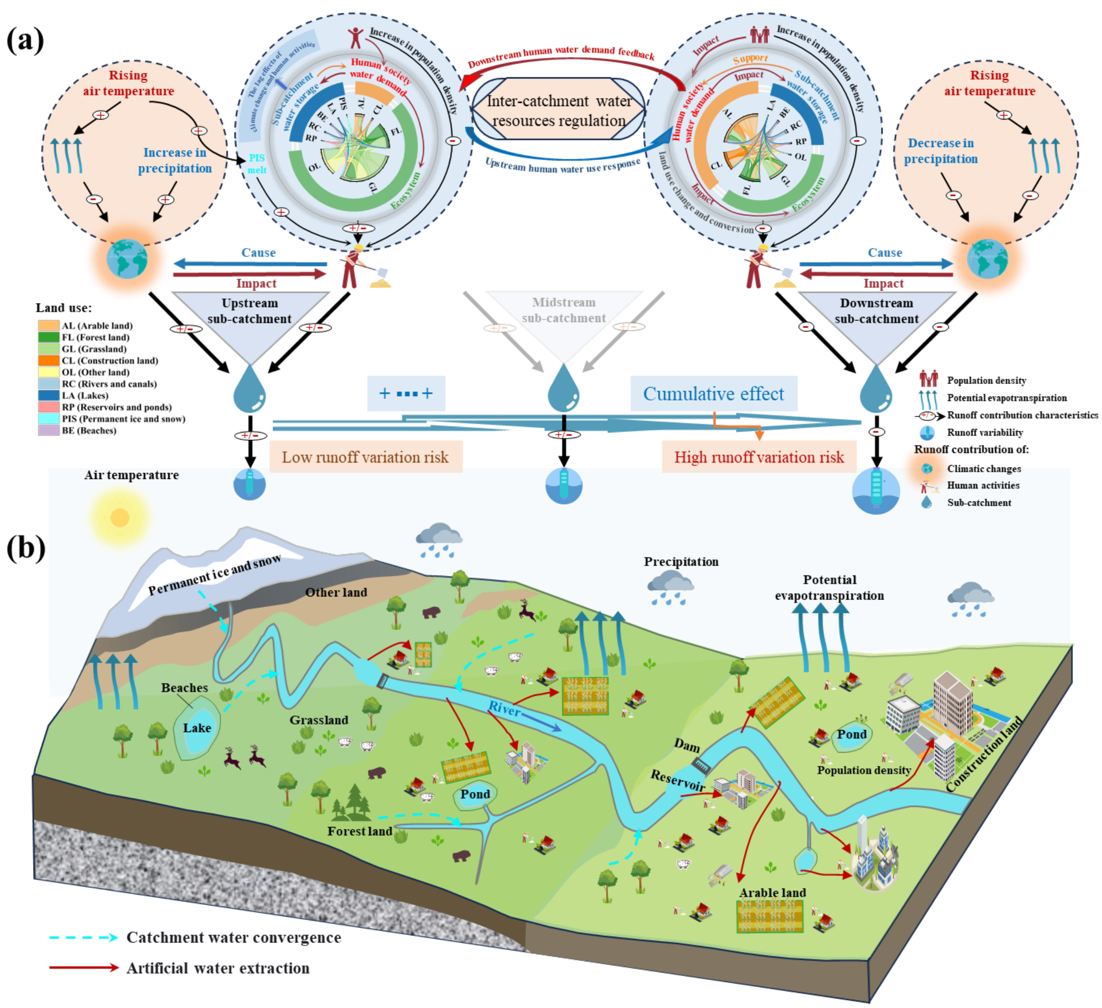
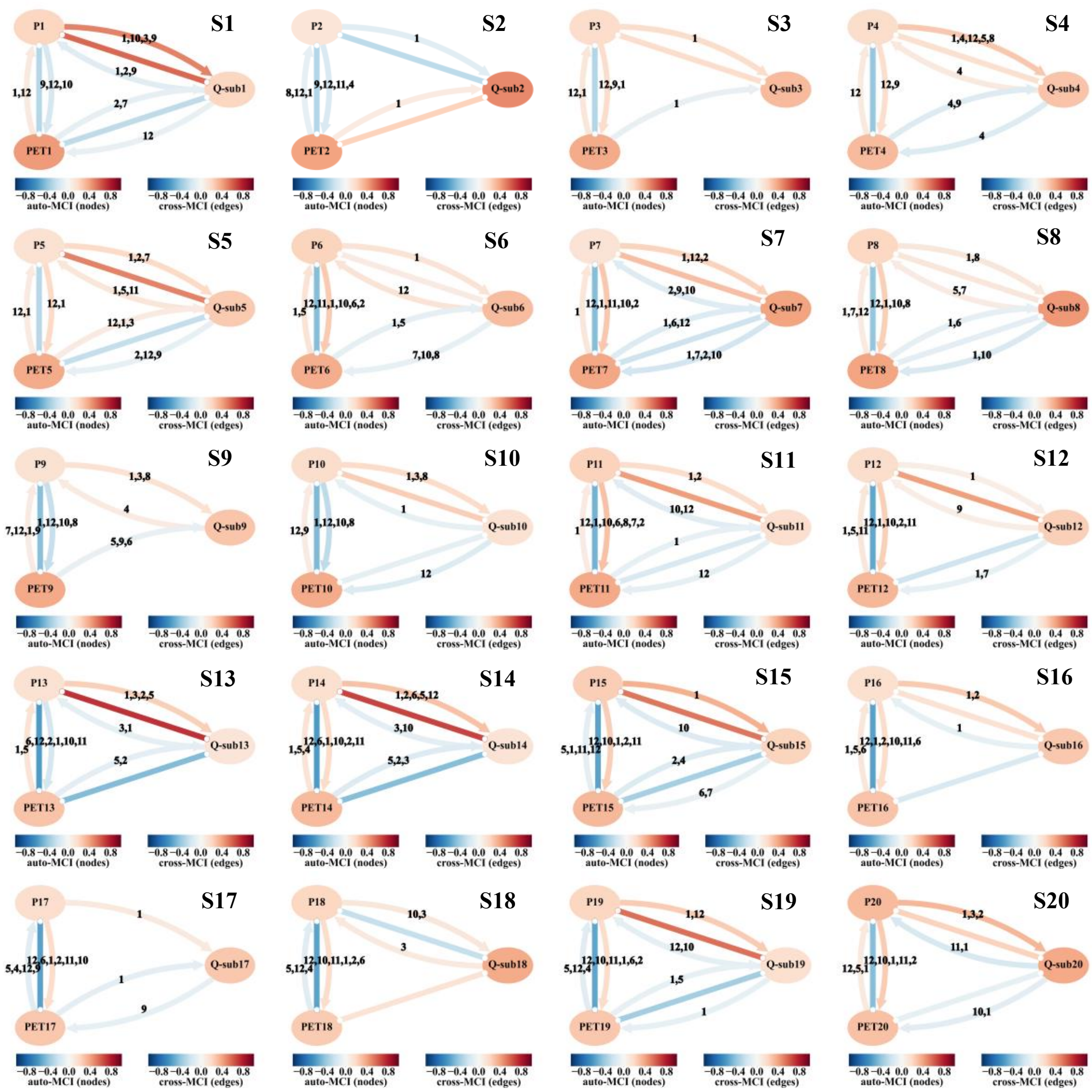


Fig. 9: Conceptual framework illustrating the upstream-downstream interaction of runoff variation in large river basins under the context of climate change and human activities. **(a):** The impacts and contribution characteristics of climatic changes and human activities on runoff variations in the upstream and downstream watersheds are described separately, along

with the interactive relationship of water resource regulation between the upstream and downstream sub-catchments. **(b):** The human activities within the upstream and downstream sub-catchments of the basin and their contribution characteristics to river runoff variations are highlighted. Overall, the demand for water resources from human activities in each sub-catchment from the upstream to the downstream within the basin gradually increases. The combined effects of climate change and human activities along the way result in higher risks of runoff variation in the downstream areas. At the same time, the demand for water resources by human societies in the downstream regions will promote the regulation of water resources between the upstream and downstream sub-catchments within the basin, thereby affecting the runoff variations in both the upstream and downstream areas.

Revised Supplementary Figures: Supplementary Fig. 18



Supplementary Fig. 18: The significant causal network among monthly runoff contributions (Q_{sub}), precipitation (P), and potential evapotranspiration (PET) across sub-catchments from 1952 to 2021, obtained through PCMCI+ analysis (significance level = 0.05, maximum time lag = 12 months). Node colors represent auto-correlation strength, while link edge colors indicate the (positive or negative) MCI coefficient strength between variables. Arrow direction and labels denote the causal relationship between time-lagged data of the source variable (with lag time in months indicated by link labels) and contemporaneous data of the target variable.

Comment 6: *I find the English should be improved.*

Response 6: We sincerely appreciate your valuable comments and suggestions. We have conducted a comprehensive language polishing of the English terminology and expressions throughout the entire manuscript. Below, we list some of the major modifications and improvements made to the English expressions.

Revised Manuscript LL 24-26: Integrating comprehensive understanding of multi-scale hydrological variability drivers and spatial interaction mechanisms is essential for advancing adaptive river basin management and sustainable water resources allocation.

Revised Manuscript LL 39-41: The combined impacts of climate change and human activities on basin-scale hydrological processes and water resources have emerged as a critical challenge for achieving sustainable socioeconomic and eco-environmental development worldwide[14].

Revised Manuscript LL 49-53: Furthermore, scholars have explored the impacts of land-surface modifications, glacial melt, and agricultural irrigation on runoff by analyzing deviations from the Budyko curve in representative catchments[25,26,27], combined with the Peter-Clark MCI Plus (PCMCI+) causal discovery algorithm[28,29,30].

Revised Manuscript LL 59-63: Recent studies have shown that the river flow distribution across approximately 29% of the global terrestrial surface has significantly shifted from downstream to upstream regions, exacerbating water scarcity in 7.4%-16.5% of downstream areas[38,39]. An increasing trend may lead to greater reliance on upstream "water tower" runoff by nearly half of the world's downstream areas[40].

Revised Manuscript LL 74-77: Given the observations in recent years of many iconic rivers that were once perennial becoming intermittent[43,44], it is imperative to conduct an in-depth attribution analysis of runoff changes in large river basins[45], particularly for the Yellow River, the world's fifth-largest river[46].

Revised Manuscript LL 120-122: For the latter 35 years (PII: 1987-2021), all sites show decreased multi-year average flow compared to the initial 35 years (PI: 1952-1986), with reductions of 24.62-733.05 $m^3 s^{-1}$.

Revised Manuscript LL 208-211: Furthermore, recent decades show a shift in water storage from natural systems (e.g., lakes, wetlands, and glaciers) to artificial ones (e.g., reservoirs and ponds), accompanied by a marked reduction in water storage capacity.

Revised Manuscript LL 256-257: However, sub-catchments regulated by large reservoirs exhibit significant monthly variations (Fig. 6b), which are predominantly driven by human regulation.

and so on).

References:

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2. Dey, P. & Mishra, A. Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions. *Journal of Hydrology* **548**, 278-290, doi:10.1016/j.jhydrol.2017.03.014 (2017).
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4. Luan, J. et al. Evaluating the uncertainty of eight approaches for separating the impacts of climate change and human activities on streamflow. *Journal of Hydrology* **601**, doi:10.1016/j.jhydrol.2021.126605 (2021).
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6. Zaerpour, M. et al. Impacts of agriculture and snow dynamics on catchment water balance in the U.S. and Great Britain. *Communications Earth & Environment* **5**, doi:10.1038/s43247-024-01891-w (2024).
7. Zaerpour, M., Hatami, S., Ballarin, A. S., Papalexiou, S. M., Pietroniro, A., & Nazemi, A. Agriculture's impact on water–energy balance varies across climates. *P Natl Acad Sci USA*, **122**(12) e2410521122 (2025).
8. Sun, C. et al. Human activities have more impacts on the recent discharge reduction of the largest tributary of the Yellow River relative to last three centuries. *Science of The Total Environment* **890**, doi:10.1016/j.scitotenv.2023.164217 (2023).
9. Wang, W., Zhang, Y. & Tang, Q. Impact assessment of climate change and human activities on streamflow signatures in the Yellow River Basin using the Budyko hypothesis and derived differential equation. *Journal of Hydrology* **591**, doi:10.1016/j.jhydrol.2020.125460 (2020).

RESPONSE TO REVIEWERS' COMMENTS

Dear Editor and reviewers,

We would like to express our sincere gratitude once again to the editor and reviewers for their insightful comments and constructive suggestions on our manuscript (COMMSENV-25-1244A) entitled "**Climate change and human activities amplify runoff variability risks in lower reaches of large rivers**". The provided comments have contributed substantially to improving the manuscript. In response to your comments point-by-point, we have carefully revised the paper and made substantial improvements. The reviewer's comments are displayed in italic font, while our response and revised text are shown in blue and black, respectively.

<u>Responses to Reviewer #1</u>

I would like to commend the authors for their substantial and thoughtful revisions. The manuscript has significantly improved in clarity, methodological rigor, and scientific contribution. I particularly appreciate the revised attribution framework, the re-quantification based on multi-year averages, and the integration of the PCMCI+ causal discovery method. These additions strengthen the overall analytical approach and support the main conclusions more robustly.

The authors have addressed the concerns raised in the previous round in a clear and constructive manner. The writing is much clearer, and the structure of the paper flows better. That said, I have a few minor comments for further refinement:

Response: We sincerely appreciate the time you have taken to review our manuscript and provide insightful comments, which have greatly improved its quality. In response to your valuable comments, we have carefully revised and refined the manuscript. Specifically, we have meticulously revised and refined the Figures to enhance their readability and interpretability.

Comment 1: Both Figure 2 and Figure 3 are quite crowded and not easy for the reader to

follow.

In Figure 2, please increase the font size, particularly for axis labels and annotations. Currently, the small text makes it difficult to read, even at full zoom.

In Figure 3, the same issue applies—at minimum, please increase the font size for the subtitles and the labels "Period 1", "Period 2", "Period 3", "Period 4", as well as "Period I" and "Period II", which are hard to read in the current format. If possible, you can consider simplifying the two figures.

Response 1: Thank you for helping us identify this issue. We have revised Figure 2 and Figure 3. Key improvements include:

(1) Enlarged font sizes for subtitles, axis labels, annotations, and specific period labels (“Period 1”, “Period 2”, “Period 3”, “Period 4”, “Period I”, and “Period II”).

(2) Reduced visual crowding by adjusting subplot spacing and applying bold formatting to key information (while keeping axis labels unbolded) for better readability.

Revised Figures: Fig. 2 and Fig. 3

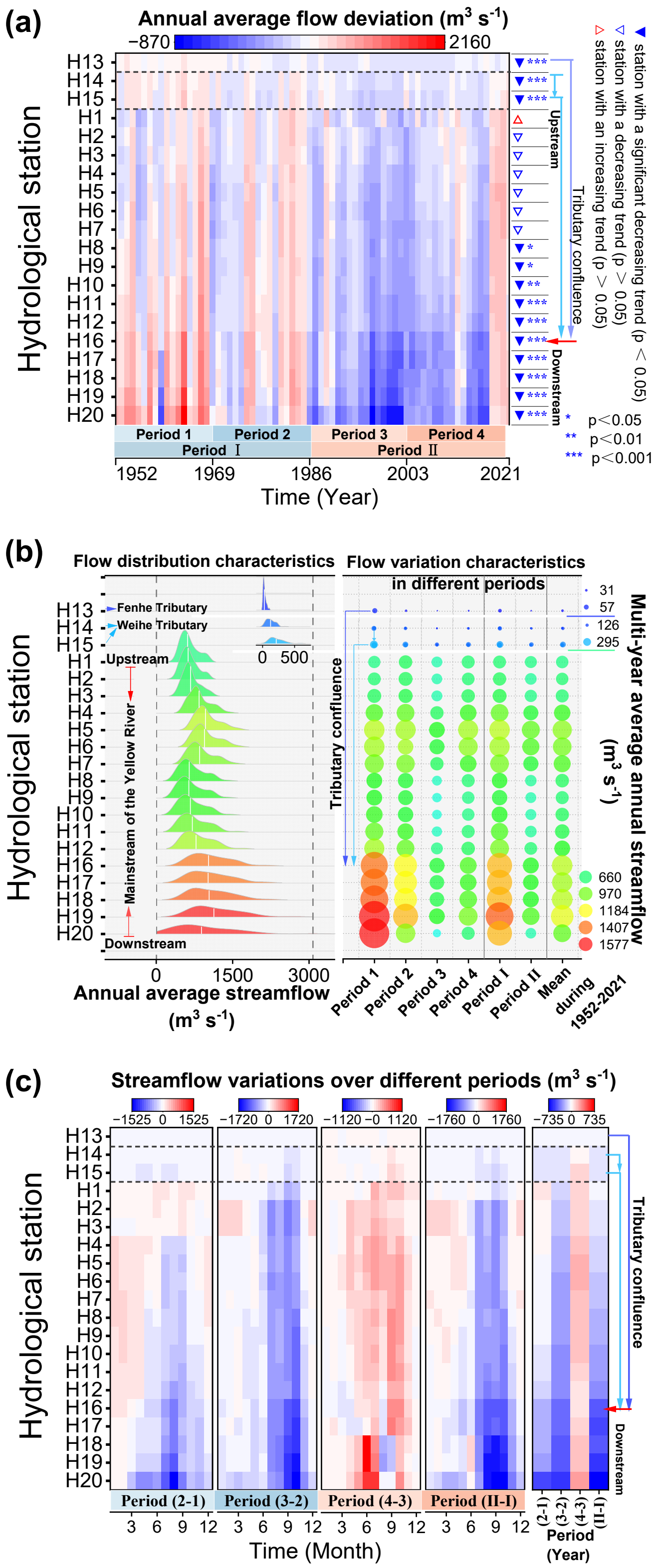

Fig. 2: The annual and monthly variation trends of flow volumes at various hydrological stations between upstream and downstream during the 70-year study period (1952-2021).

(a): The annual variation trend in the deviation values of flow volumes at each hydrological station. Asterisks denote significance levels (* for p ≤ 0.05, ** for p ≤ 0.01, *** for p ≤ 0.001). **(b):** The distribution characteristics of the annual average flow volumes at each hydrological station for the years 1952-2021, as well as the multi-year average variation trends during different periods. **(c):** The monthly and annual variation amounts of the multi-year average flow volumes at each hydrological station during different periods.

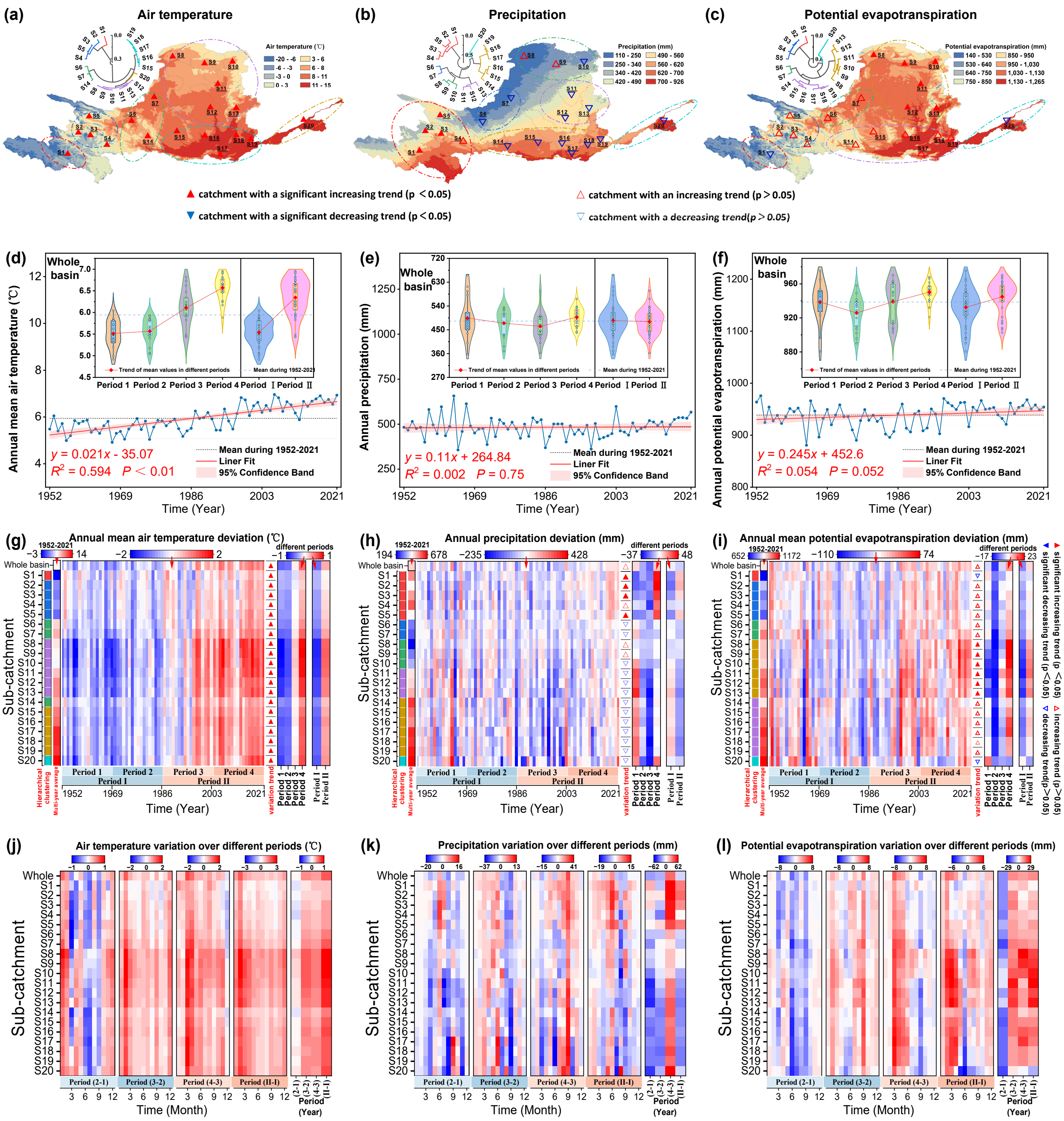

Fig. 3: Annual and monthly variation trends of air temperature, precipitation and potential evapotranspiration in the Yellow River Basin and sub-catchments over the 70-year (1952–2021) study period. (a-c): Spatial distribution of annual means of air temperature, precipitation, and potential evapotranspiration (1952-2021), alongside their annual variation trends of each sub-catchment. The inset illustrates the similarities and differences in interannual variability of these climate factors across sub-catchments. **(d-f):** Annual trends (1952-2021) of these climatic factors in the whole basin, along with their multi-year mean shifts during distinct periods. **(g-i):** The annual variation trends (1952-2021) of the deviation values of air temperature, precipitation, and potential evapotranspiration in each sub-catchment; and the corresponding variation trends of the multi-year average values across different periods. **(j-l):** The variations in monthly and annual average values of these climatic factors between different periods for the whole basin and each sub-catchment area.

Comment 2: Figure 8 – Inconsistent Color Mapping:

Figure 8 – Inconsistent Color Mapping: Please double-check the colormap used to display MCI values in Figure 8. There appears to be an inconsistency in how the values are represented. In some cases, the color scale implies a range from -1 to 1, using diverging blue-red tones (suggesting both positive and negative correlations), while in other parts, the scale seems to reflect a range from 0 to 1, which is appropriate for MCI values that should be non-negative. This inconsistency can be misleading to readers interpreting the causal strengths. Please ensure that the color scale is consistent and correctly reflects the theoretical range of MCI values (typically [0, 1]), and update the legend and caption accordingly.

Response 2: We sincerely appreciate your constructive comments. We have carefully revised Figure 8 with the following improvements:

(1) Standardized the color mapping across all subplots, making targeted revisions to the color schemes in Figures 8d–f and their legends. This ensures consistent representation of MCI values through uniform color scales across the entire Figure 8.

(2) Added clear subplot captions to facilitate reader comprehension.

Revised Figures: Fig. 8

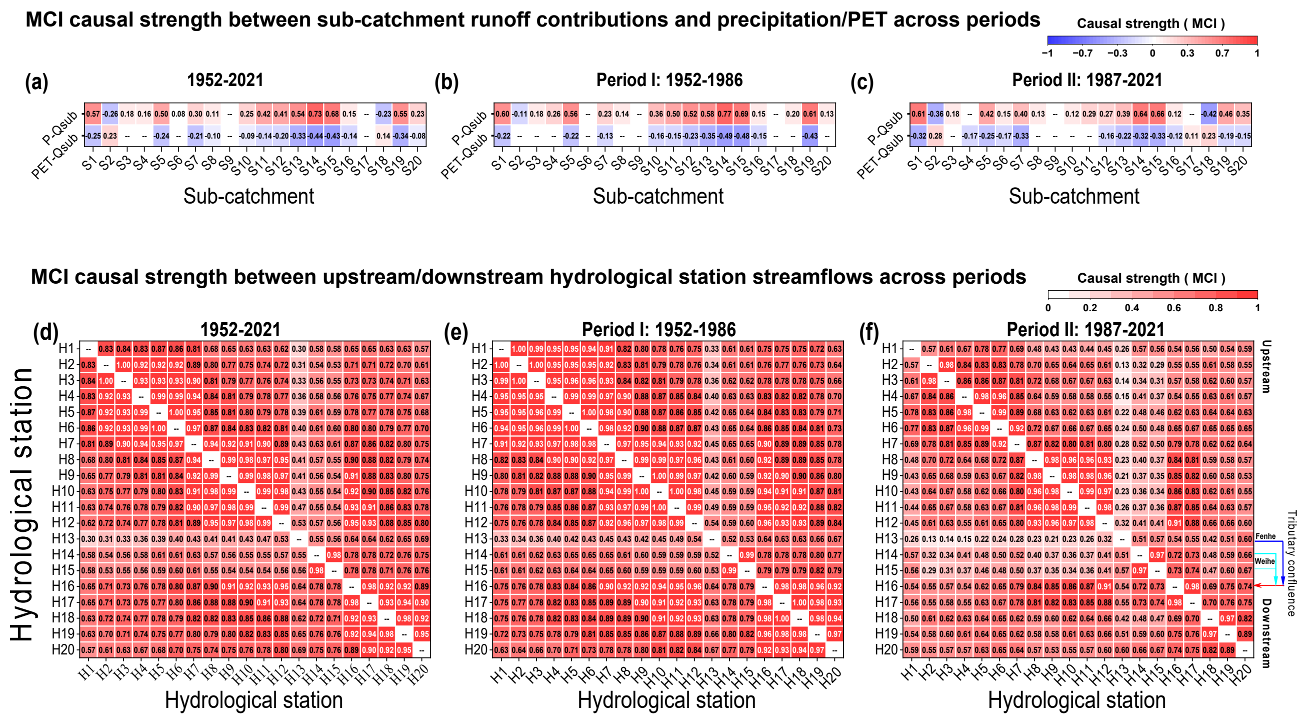

Fig. 8: Causal relationships derived from the PCMCI+ algorithm between runoff contributions and Budyko water-energy balance components (precipitation and potential evapotranspiration) across sub-catchments, as well as between runoff at upstream and downstream hydrological stations. Subfigures **(a)**, **(b)**, and **(c)** respectively present the MCI causal association strength between runoff contributions of each sub-catchment and contemporaneous precipitation/potential evapotranspiration during **(a)** 1952–2021, **(b)** 1952–1986, and **(c)** 1987–2021, with missing values indicating non-significant causal association at the 0.05 significance level; Subfigures **(d)**, **(e)**, and **(f)** show the MCI causal association strength between contemporaneous streamflows of upstream and downstream hydrological stations for the same three periods, respectively.

Comment 3: Sub-catchment Labels in Figures:

Sub-catchment Labels in Figures: In several figures (e.g., Figures 2, 4, 5, and 6), sub-catchments are labeled using two-letter abbreviations. While this may be meaningful to the authors, it can be confusing for readers unfamiliar with the basin. I recommend consistently labeling the sub-catchments using the standardized identifiers (S1 to S20), as introduced in Figure 1. This labeling system is intuitive, reflects the sub-catchments' order along the main *river course, and would greatly enhance the readability and interpretability of the figures across the manuscript.*

Response 3: Thank you for your comments. We have revised and improved all labels in Figures 2-8. Details are as follows:

(1) In Figures 2 and 8d–8f: Letter abbreviations represent hydrological station names, which differ from the sub-catchment identifiers (S1–S20). To clarify the upstream/downstream sequence, we have replaced the names of all hydrological stations in the entire manuscript and in the figures with new hydrological station identifiers (H1-H20). Additionally, "Upstream" and "Downstream" annotations were placed at corresponding station locations within these figures.

(2) In Figures 3, 5, and 6: Axis labels directly display the standardized sub-catchment identifiers (S1–S20) and required no modifications.

(3) In Figures 4d–4i: Letter abbreviations indicate land use types, which have been fully documented with explanatory notes within the respective figures.

Revised Figures: Fig. 2, 4, 5, 6, and 8

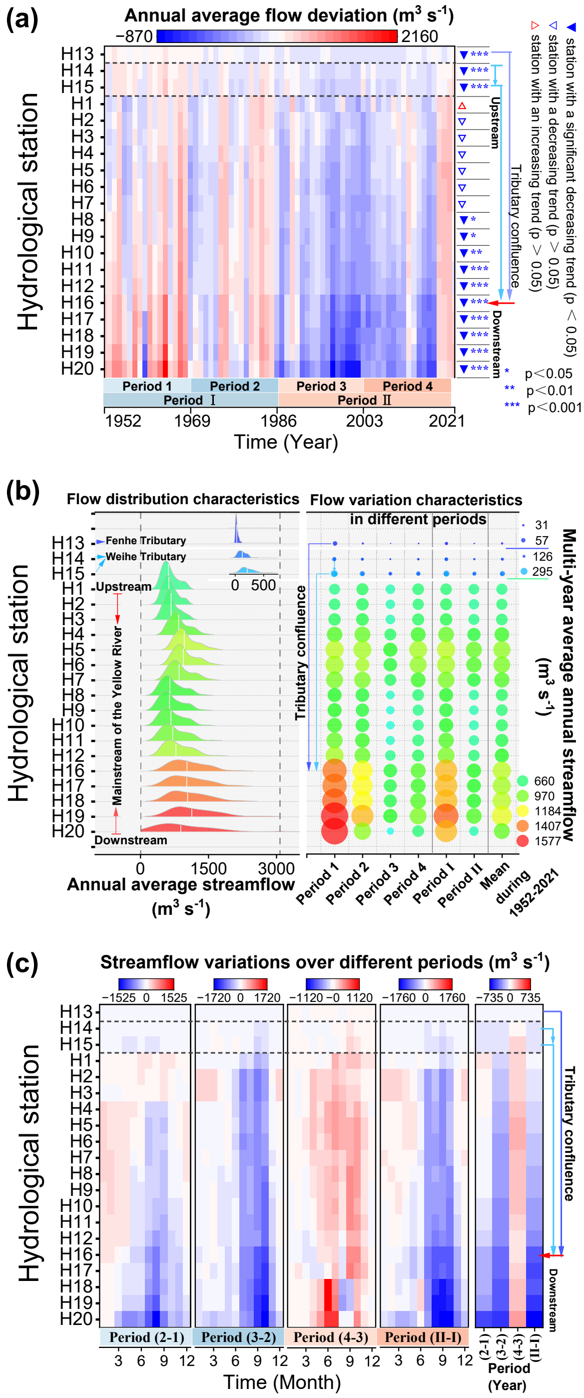

Fig. 2: The annual and monthly variation trends of flow volumes at various hydrological stations between upstream and downstream during the 70-year study period (1952-2021). **(a):** The annual variation trend in the deviation values of flow volumes at each hydrological station. Asterisks denote significance levels (* for $p \leq 0.05$, ** for $p \leq 0.01$, *** for $p \leq 0.001$). **(b):** The distribution characteristics of the annual average flow volumes at each hydrological station for the years 1952-2021, as well as the multi-year average variation trends during

different periods. **(c):** The monthly and annual variation amounts of the multi-year average flow volumes at each hydrological station during different periods.

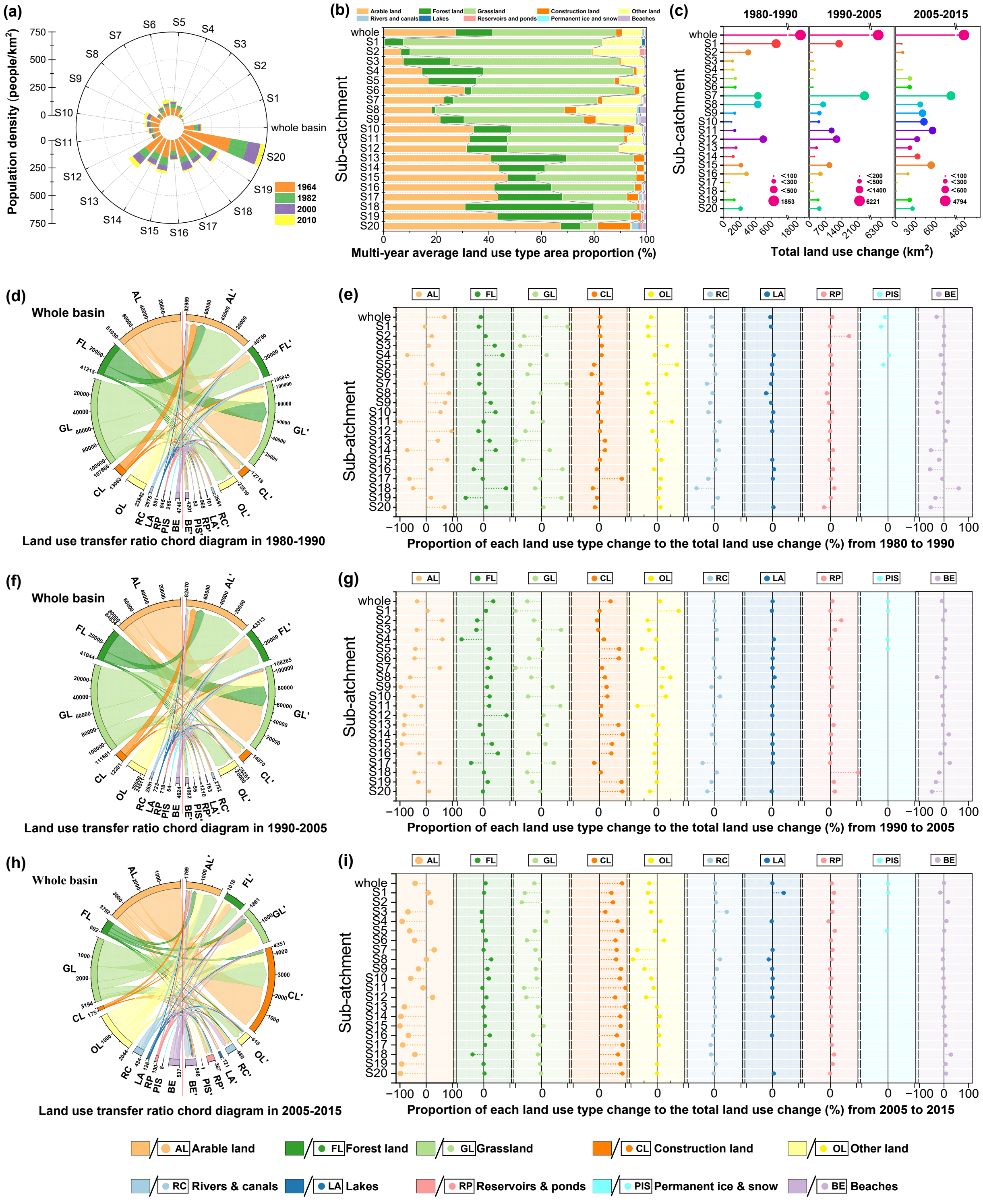

Fig. 4: The population density trends, as well as the proportions, transfer volumes, and changes in various land use types across the whole basin and sub-catchments. (a): The

population density distribution and changes for the years 1964, 1982, 2000, and 2010. **(b):** The proportions of the average areas of different land use types in each watershed for the periods around 1980, 1990, 2005, and 2015. **(c):** The total land use changes that occurred in each sub-catchment during the periods 1980-1990, 1990-2005, and 2005-2015. The transfer volumes of each land use type in the whole basin during the periods 1980-1990 **(d)**, 1990-2005 **(f)**, and 2005-2015 **(h)**. The proportions of different land use type changes to the total change in each sub-catchment during the periods 1980-1990 **(e)**, 1990-2005 **(g)**, and 2005-2015 **(i)**.

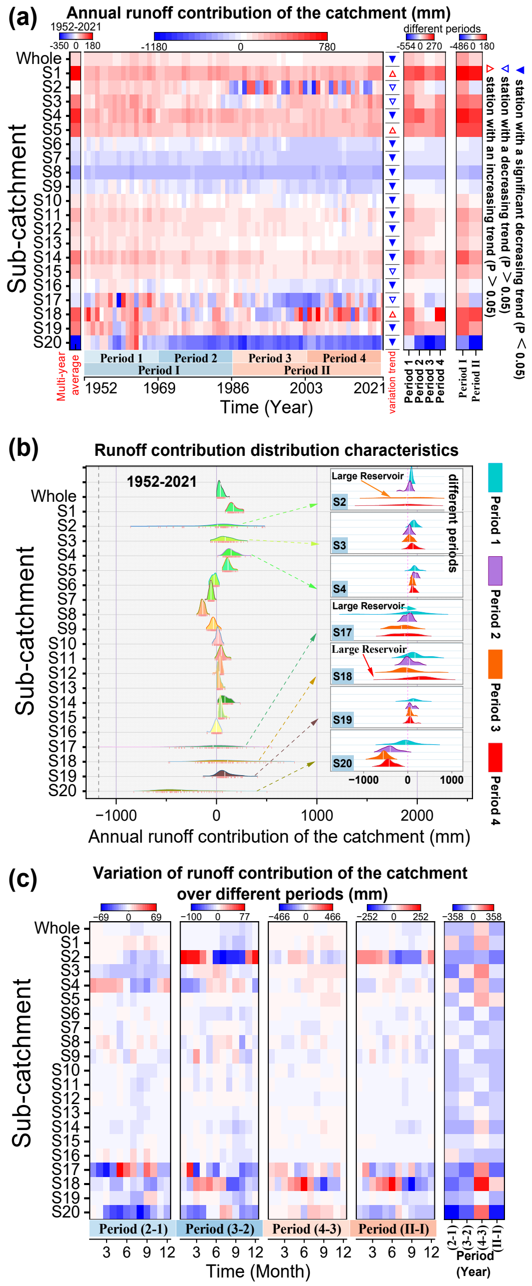

Fig. 5: The annual and monthly variation trends of runoff contribution volumes in the whole basin and each upstream and downstream sub-catchment during the 70-year study period (1952-2021). (a): The annual variation trend of runoff contribution volumes in each sub-

catchment, as well as the multi-year average variation trends during different periods. **(b):** The distribution characteristics of the annual average runoff contribution volumes at each sub-catchment for the years 1952-2021, with an inset illustrating changes in the distribution characteristics of the annual average runoff contributions over different periods. **(c):** The monthly and annual variation amounts of the multi-year average runoff contribution volumes in each sub-catchment during different periods.

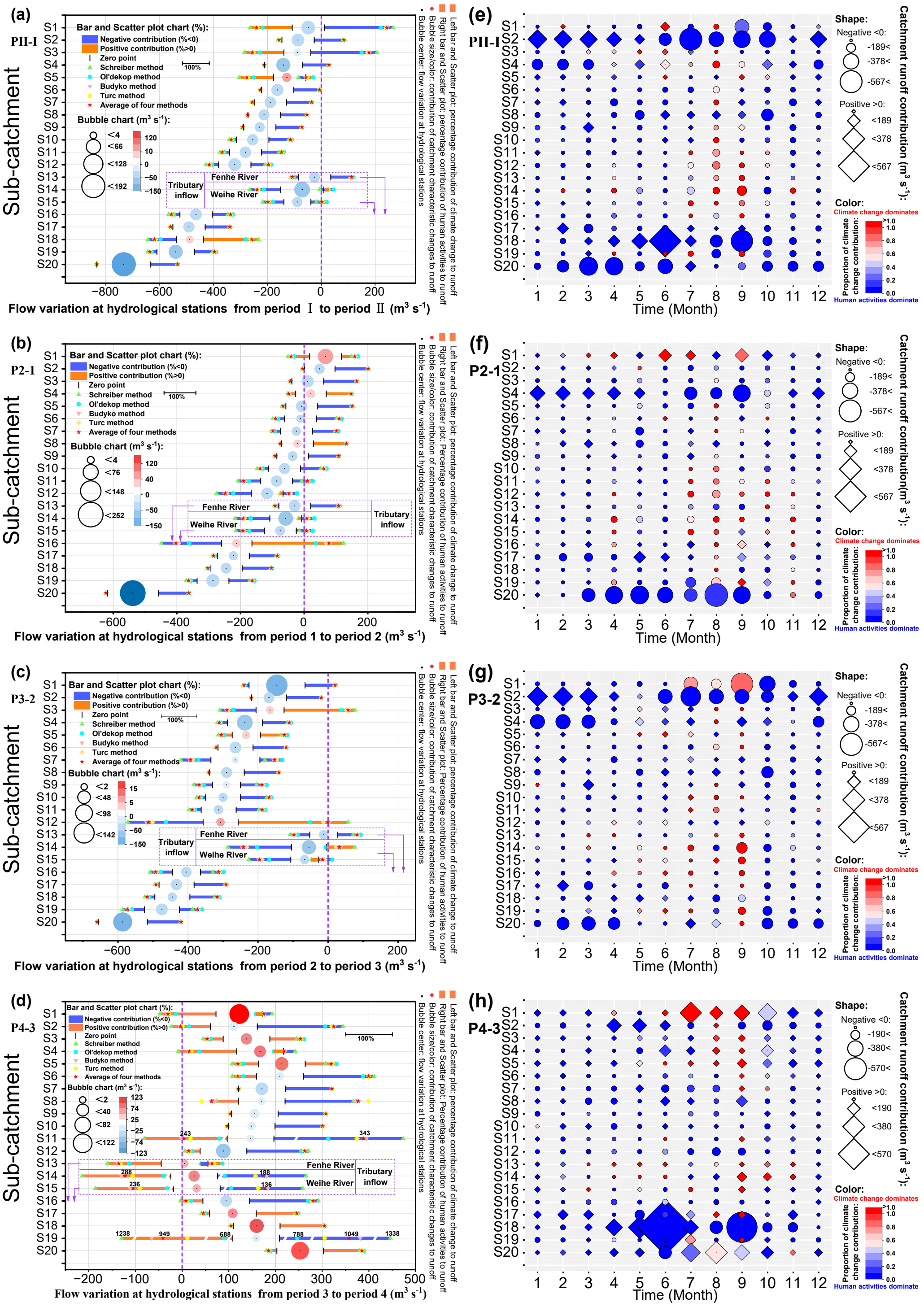

Fig. 6: The annual and monthly contribution rates of climate change and human activities to the changes in runoff contribution volumes in each sub-catchment. The multi-year average annual scale runoff contribution volume changes (bubble chart) for upstream and downstream sub-catchments from period I to period II **(a)**, period 1 to period 2 **(b)**, period 2 to period 3 **(c)**, and period 3 to period 4 **(d)**, the percentage contributions (%) of climate change and human activities to the changes in runoff contribution volumes (bar chart and scatter plot), and the flow volume changes at the corresponding hydrological stations at the outlets of each sub-catchment (center points of bubbles). The multi-year average monthly scale runoff contribution volume changes (shape and size of points) for upstream and downstream sub-catchments from period I to period II **(e)**, period 1 to period 2 **(f)**, period 2 to period 3 **(g)**, and period 3 to period 4 **(h)**, and the proportion of the contribution of climate change to the total changes in runoff contribution volume (color of points).

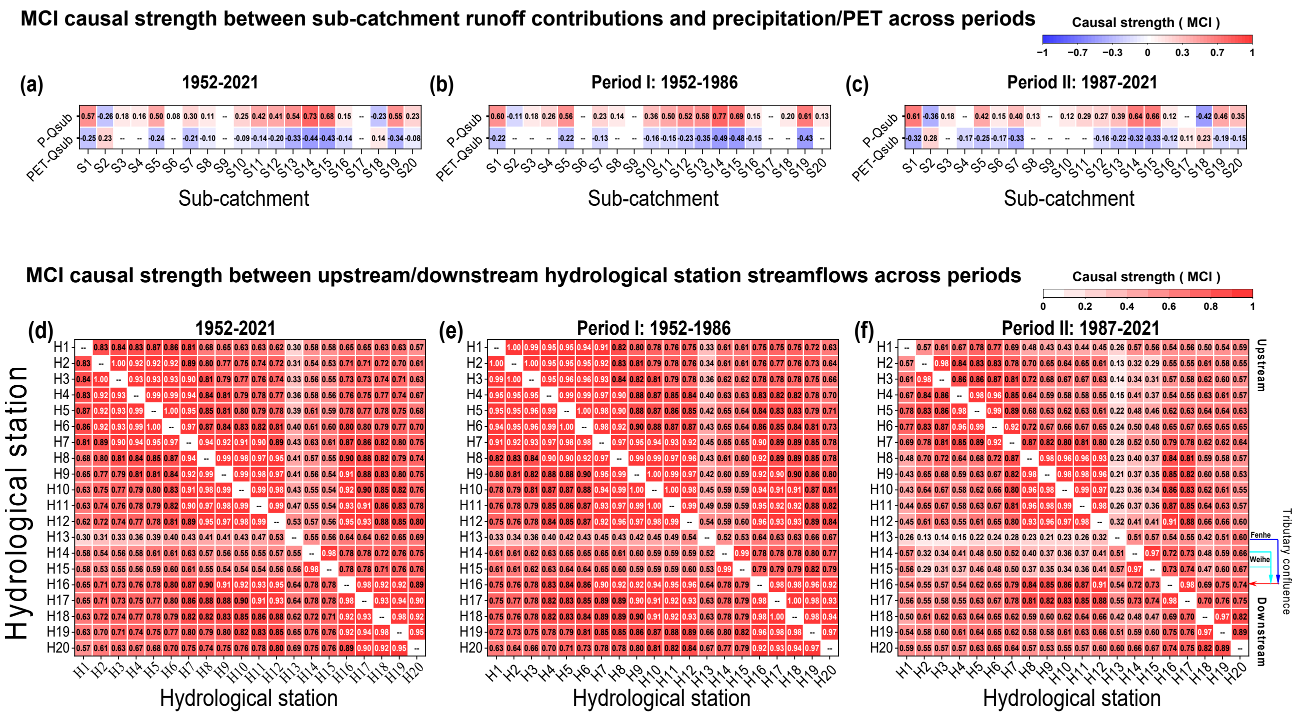

Fig. 8: Causal relationships derived from the PCMCI+ algorithm between runoff contributions and Budyko water-energy balance components (precipitation and potential evapotranspiration) across sub-catchments, as well as between runoff at upstream and downstream hydrological stations. Subfigures **(a)**, **(b)**, and **(c)** respectively present the MCI causal association strength between runoff contributions of each sub-catchment and contemporaneous precipitation/potential evapotranspiration during **(a)** 1952–2021, **(b)** 1952–1986, and **(c)** 1987–2021, with missing values indicating non-significant causal association at the 0.05 significance level; Subfigures **(d)**, **(e)**, and **(f)** show the MCI causal association strength

between contemporaneous streamflows of upstream and downstream hydrological stations for the same three periods, respectively.

Comment 4: The referencing of figure 1 could be improved.

The referencing of figure 1 could be improved. Figure 1 is first mentioned at the end of the Introduction, but its relevance and placement are unclear. It would help to refer to it later in the "Data and data processing" when describing the study region or move its citation to better align with surrounding content. I would also suggest change the title of subsection to "Data sources and processing"

Response 4: We are truly grateful for your constructive comments. This study references Figure 1 in three locations: the end of the Introduction, the Study area section, and the "Data sources and processing" section. However, we still retain the practice of first introducing the map of the study region (i.e., Figure 1) at the end of the Introduction. This is primarily because the journal's layout places the Methods section after Results and Discussion. If Figure 1 were first mentioned later in "Data sources and processing", it would be labeled as "Figure 9", which clearly violates the logical order for presenting a study area map. Therefore, it is more appropriate to first introduce it before the Results section, specifically at the end of the Introduction.

- Naturally, we have also appropriately expanded the descriptive content about the study area (Figure 1) at the end of the Introduction.
- Additionally, we have changed the section title from "Data and data processing" to "Data sources and processing" throughout the manuscript.

Revised Manuscript LL 93-94: Introduction section

Therefore, this study focuses on the Yellow River Basin and twenty sub-catchments delineated based on the main stem and major tributaries (Fig. 1).

Revised Manuscript LL 486: Data sources and processing

Comment 5: *With the above minor revisions, particularly those aimed at improving figure readability, I believe this paper will make a valuable contribution to the field of hydroclimatic change and river basin management.*

Response 5: We are grateful for your helpful comments. According to your valuable comments, we have revised and improved the manuscript, with particular attention to making meticulous revisions to the figures.

Responses to Reviewer #2

I am happy to accept this manuscript.

Response: We are deeply grateful for the time you have taken to review our manuscript and for your valuable comments.