We deeply appreciate the detailed and constructive comments provided by the three anonymous reviewers. Following their suggestions and comments, we have extensively revised the manuscript and provided a point-to-point response to each comment. The original comments are in **bold** font, our response is in regular font, and the changes in the text are in blue.

Comment 1

Sang et al. studied the interprovincial connections of green water. They quantified this by calculate the precipitation of each province from the green water inside or outside the province. The work is based on the data generated from a previous particle tracking work. Authors connect the results with social-economic effects, which is very interesting and novel. The structure and writing of the paper are clear. However, I have some thoughts as follows:

Response: Thank you for taking your time to review our study and provide feedback and comments. Following the suggestions and comments, we have extensively revised the manuscript and provided a point-to-point response to each comment. The original comments are in **bold** font, our response is in regular font, and the changes in the text are in blue.

1. **I don't think authors have clear enough introduction about how they connect the green water with the social-economic value. The introduction is in lines 140-175, but not clear. There are even no dimensions of the variables, and it is hard to know the relationship between different variables in the equations.**

Response: Thank you for the comments.

We apologize for the confusion regarding the introduction about the connections between green water and socio-economic values.

The connection of green water with socio-economic value can be reflected in the cascade that green water from source region forms precipitation in sink region, then precipitation recharges water resources and sustain economic activities, human livelihood and crop growth. We estimated the green water contribution on social-economic values in terms of surface water resource volume, economic output (GDP), population and food production.

In the revision, we added a more detailed introduction about the connections between green water and socio-economic values in Figure 1 and section Method. Please see the revised texts and figure below.

Green water from upwind source provinces flows and precipitates downwind to recharge water resources, and therefore sustains socio-economic activities in sink provinces, as depicted in Fig. 1. Consequently, precipitation, water resources, and socio-economic factors such as economic activities, human livelihood, and crop production in sink provinces rely on green water exported from source provinces. Changes in green water may affect water resource volume, and then impact economic activities, livelihood, and crop production through water supply.

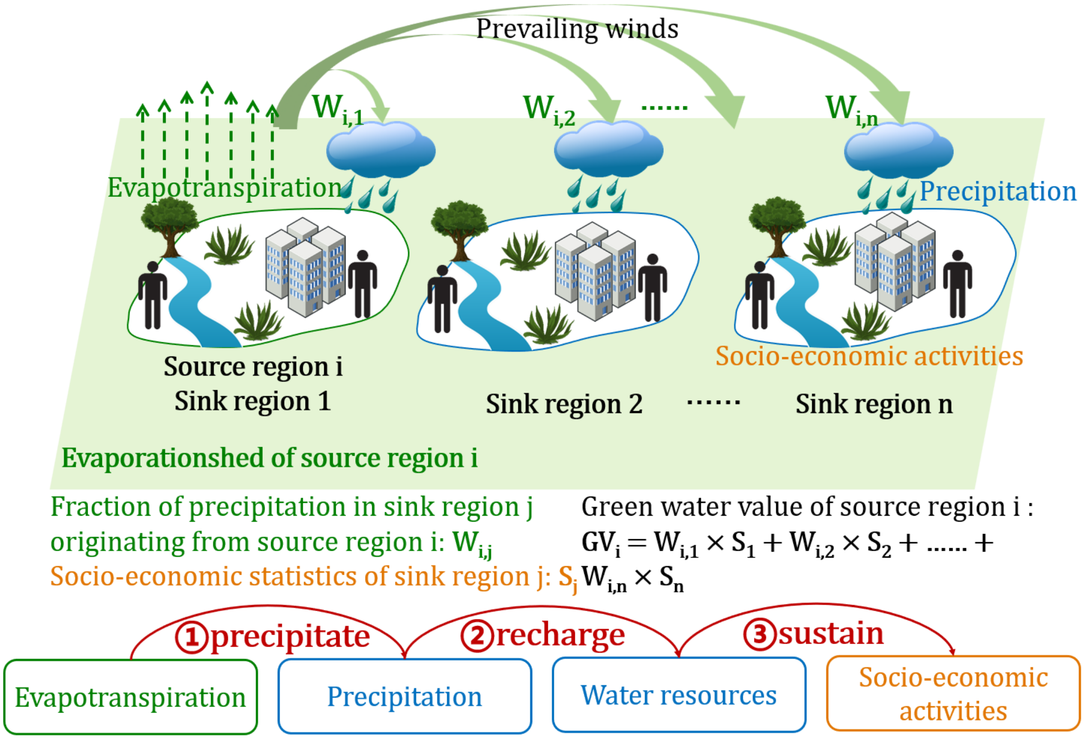

Figure 1. A conceptual diagram depicts the teleconnection of green water flows and their socio-economic contributions in a cascade manner. Evapotranspiration (green dotted arrows) from source region *i* flows downwind with prevailing winds (green thick arrows) and precipitates in sink region *n*, which recharges water sources and sustains socio-economic activities in sink regions.

2. **It looks like authors assume linear relationships between water and all the social-economic indices. I am not quite sure if this is rigorous. For example, whether the food productivity has the positive, linear relationship with water? Similar question to other social-economic indices.**

Response: Thank you for the comments.

We apologize for the confusion regarding the assumption about the relationships between green water and socio-economic indices.

In our assessment, we assume that all socio-economic indices (i.e. water resources volume, economic output, population and food production) are sustained by precipitation originating from green water from source regions. The socio-economic value of ET was calculated using the average values of various socio-economic indicators from 2008 to 2017 to match the climatological moisture trajectories from 2008 to 2017. Any temporal changes in water use efficiency per socio-economic variables are not included in this calculation. Therefore, the positive or negative relationship between socio-economic indicators and water use through time does not affect the value assessment of green water.

We discussed this point in the revision, and the revised texts are shown below.

Moreover, the resulting moisture trajectory data only represent the climatologically average moisture trajectories and ET (Li et al., 2023), neglecting the interannual variability in moisture flow trajectory, e.g., those induced by the influence of extreme weather events or ENSO (Zhao and Zhou, 2021). The interannual variations in green water flow may affect DPR and DSR in some provinces. Human adaptation tends to buffer the impacts of interannual variations on the socio-economy through water resource management such as reservoirs, dams, and other infrastructure. Accounting for interannual variations in green water flows and their socio-economic contribution is worth further investigation.

In future studies, the dynamic linkage between green water, water resources and economic development can be assessed annually by using a long-term moisture tracking dataset with a separation of water sources consumed by socio-economy (surface and groundwater).

3. **For the sections of sources and sinks of green water (sections 3.1 and 3.2), it is hard to say they are really novel as it looks like some known results with a new wrapper. You are talking about the evapotranspiration circulation by adding the ‘interprovincial’ concept.**

Response： Thank you for the comments.

Sections 3.1 and 3.2 present the results of interprovincial green water transfer. Although many research analyzed the spatial pattern of moisture recycling in China from amphoteric and hydrological sciences, they identified moisture source and sinks at the grid (Zhang et al., 2023), river basins (Wang et al., 2023), and ecological regions scale

(Xie et al., 2024). There is a clear understanding of the large-scale spatial pattern of moisture circulation, few studies focus on quantify moisture recycling at the administrative district scales, which is important for the water management. Therefore, this study applies moisture recycling techniques to inform green water transfer at among provinces, which is previously less known but important for regional water resources management.

With this purpose, Sections 3.1 and 3.2 can help water resources managers understand the moisture recycling and the network of interprovincial moisture recycling is the basis of the socio-economic contribution of green water in each province. In the revision, we streamlined 3.1 and 3.2, and merged them. The revised texts are shown below:

3.1 The interprovincial green water flows in China and their directions

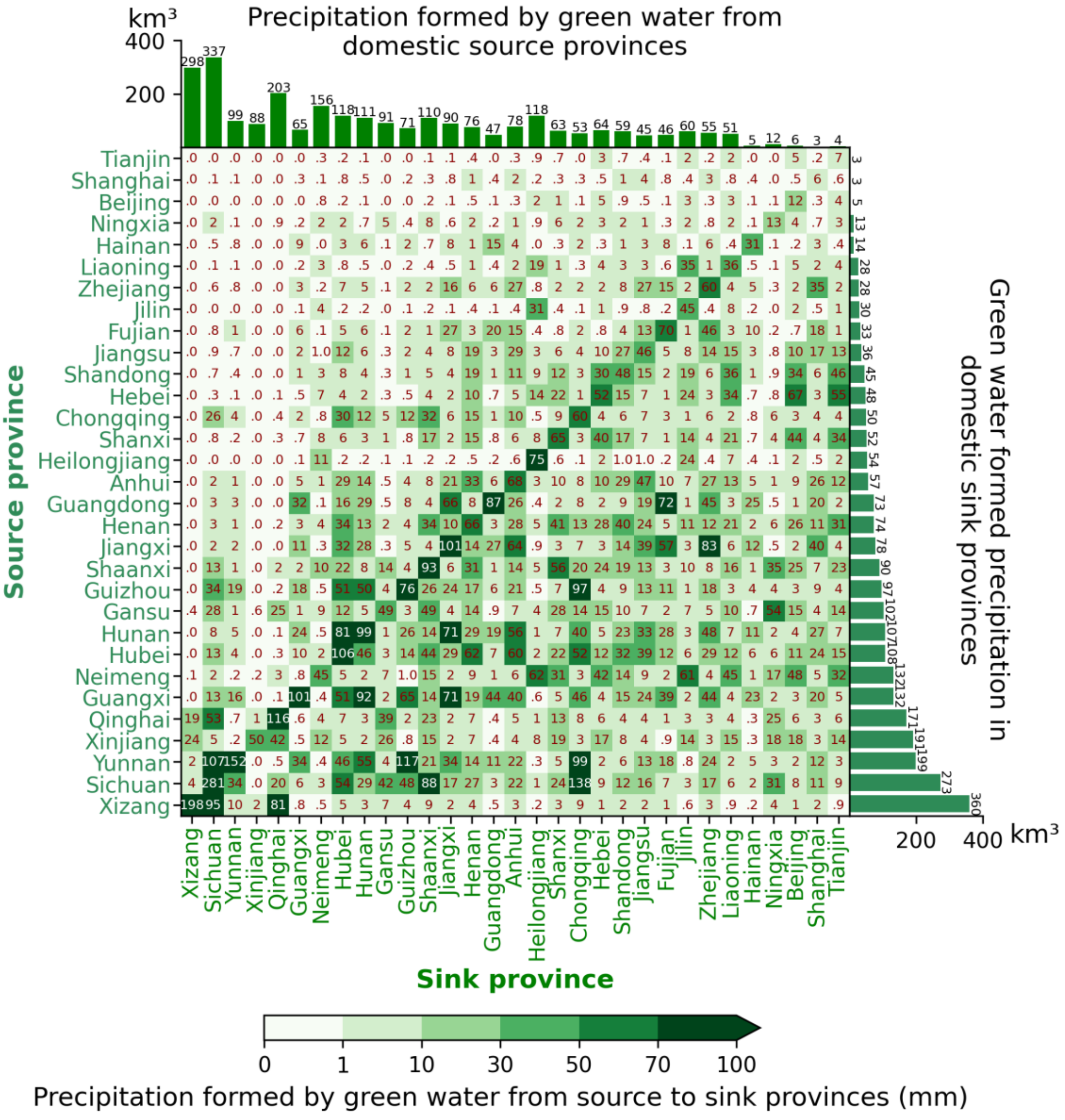

Figure 2. Interprovincial green water flows in China. The heat map denotes precipitation in sink province generated by green water from a source province (mm). The right bar shows domestic

precipitation (km^3) formed by green water from each source province. The top bar shows precipitation in each sink province formed by green water from domestic source provinces (km^3).

Green water exported from a source province forms precipitation in different sink provinces in China, and precipitation in a sink province originates from green water in different source provinces. Therefore, different provinces in China, acting either as sources or sinks, are interconnected through moisture recycling and established an interprovincial network (Fig. 2).

A large fraction of green water exported from each source province is retained locally to generate precipitation (diagonal cells in Fig. 2). The precipitation recycling ratio (PRR), the ratio of precipitation generated by local green water to total precipitation, reflects how much green water of each source province contributes to its own precipitation (Fig. A2c). Xizang has the highest PRR of 0.345, followed by Qinghai (0.341) and Sichuan (0.297). Besides local recycling, green water predominantly flows and generates more precipitation in neighboring provinces and less in distant provinces. For example, green water from Sichuan forms high precipitation in neighboring provinces such as Chongqing (138 mm), far surpassing other distant sink provinces (< 88 mm).

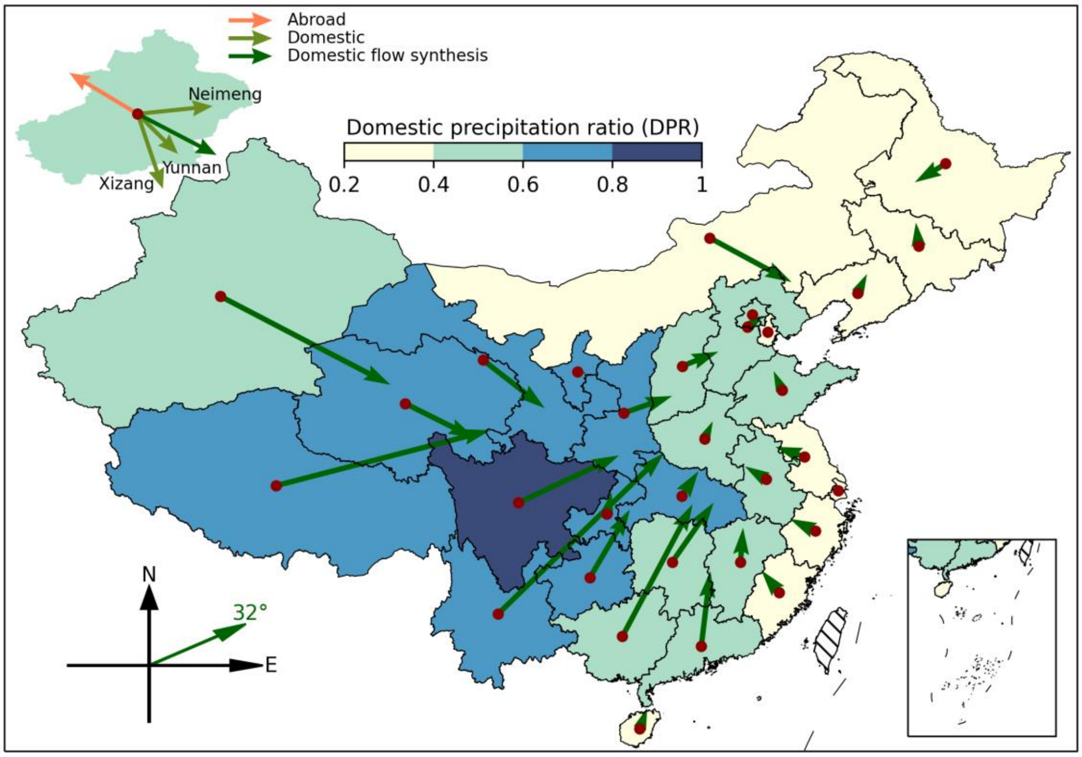

Figure 3. Direction of green water flows from each source province in China. Green arrows indicate the average direction of domestic green water flows, denoted as a vector starting from a source (the geometric center in red points) to sink provinces and with its length representing the

amount of precipitation formed by green water. The face colors on the map represent fractions of green water formed precipitation within China of each source province (DPR). The upper left corner is a schematic diagram for green water flows from Xinjiang. The lower left corner is the composite flow direction of interprovincial green water of all provinces.

The direction of interprovincial green water flow can be visualized as a composite direction averaging all domestic green water flows from each source province, which are mainly determined by atmospheric wind conditions, source location, and green water volume (Fig. 3). Overall, the average direction of all interprovincial green water flows is at 32° northeastward (32° north off the east direction), suggesting green water within China is transported to the north and east directions owning to combined effects of monsoons and westerly.

Green water exported by source provinces contributes to precipitation both within and outside China. We defined the domestic precipitation ratio (DPR) as the ratio of green water that formed precipitation in China to each province's total green water export to represent their relative importance to China's precipitation (Fig. A2a). Green water from provinces in western and central China mainly flows eastward under the influence of prevailing westerlies, which extend their evaporationsheds eastward to cover a large territory of China and generate more precipitation within China (Fig. 3). For instance, green water from Xizang, the largest exporter in China, produces the largest domestic precipitation (360 km^3) (right bar on Fig 2) with a high DPR of 0.74, contributing to precipitation in other 30 provinces with varying extents (0.2 to 95 mm). Similarly, the green water from southern provinces is affected by the Indian Ocean Monsoon (southwest monsoon), which drives green water flowing northeastward. With a substantial volume of green water, these southern provinces contribute significantly to domestic precipitation. In contrast, green water from eastern coastal or northwest border provinces goes to the northwest primarily attributed to the East Asian Monsoon (southeast monsoon) (Cai et al., 2010). As a result, most evaporationsheds laid outside China generate less domestic precipitation but more outside the country, resulting in a lower DPR, such as Fujian (DPR 0.31) and Heilongjiang (DPR 0.23). The northern provinces are influenced by westerly winds and winter monsoon from Siberia (Sun et al., 2012), causing predominantly southeastward flow of green water. However, evaporationsheds of these provinces mainly cover the Pacific Ocean, resulting in a relatively low DPR despite their substantial volume of exported green water. While some inland provinces have a high DPR because their evaporationsheds overlap with mainland China, the low green water volume (Fig. A4) limits their domestic precipitation contribution (e.g., Gansu and Ningxia with DPR of 0.72 and 0.66, respectively).

Furthermore, precipitation in sink provinces originates from both domestic and foreign green water sources. Sichuan (337 km^3), Xizang (298 km^3), and Qinghai (203 km^3) are the top 3 provinces importing the largest volume of green water from domestic sources due to the large ET from themselves and neighboring provinces (top bar of Fig 2). To quantify the relative importance of domestic sources, we defined the domestic source ratio (DSR) in each province as the sum of precipitation contribution from domestic sources divided by total precipitation (Fig. A2 (b)). DSR is related to each province's precipitationshed (i.e., upwind region contributing evaporation to a specific location's precipitation) (Keys et al., 2014) and the included domestic green water exporters. The highest DSR found in Qinghai (0.86) and Ningxia (0.82) is because their precipitationsheds include large domestic green water exporters like Xinjiang and Xizang, which supply considerable green water traveling eastward. Conversely, Hainan (0.07) and Guangdong (0.14) in coastal areas have lower DSR because their precipitationsheds are primarily located in oceans and other countries due to the influence of the summer monsoon (Cai et al., 2010).

4. **Authors said the data are high quality data from previous studies. I think a bit more introduction is necessary.**

Response： Thank you for the comments.

In the revision, we added a more detailed introduction about the UTrack moisture tracking dataset. The revised texts are shown below:

This study used the moisture trajectory dataset generated by the Lagrangian moisture tracking model "UTrack-atmospheric-moisture" driven by ERA5 reanalysis data. The model is the state-of-the-art moisture tracking model, producing more detailed evaporation footprints due to the high spatial resolution and reduced unnecessary complexity (Tuinenburg and Staal, 2020). The dataset provides monthly mean moisture flows at the global scale with a spatial resolution of 0.5° for 2008-2017, expressed as the fractions of evaporation from a source grid allocated to precipitation at a sink grid (Tuinenburg et al., 2020). It has been widely used in moisture recycling research with various spatial scales, such as precipitation source of the grid (Staal et al., 2023; Wei et al., 2024; Zhang et al., 2023) and basin scale (Wang et al., 2023), and moisture transport between nations (Rockström et al., 2023). The moisture trajectory dataset was used in conjunction with the multi-year monthly mean ET of 2008–2017 from the ERA5 reanalysis dataset to estimate precipitation in a sink grid originating from a source grid.

5. **It is a long-term dataset. So why not analyze the temporal variations of these teleconnections? I think this is more important to audience. The average state is also important, but they are the natural pattern which are caused by the long-term climatic conditions. We should know this basic pattern, but we cannot change it much. The more important thing is the temporal variations which represent the variations caused by some interannual variations of natural conditions or by man-made climate change. This is important to inform the future social-economic development, e.g., if such variations are good or bad and if we need actions to control or facilitate such variations.**

Response： Thank you for the comments.

We totally agree with that temporal variations of these teleconnections are very important for the social-economic development and water management. However, the available UTrack moisture tracking dataset only provides multi-year monthly mean state of moisture flow for 2008–2017, preventing us from analyzing interannual variations in moisture trajectory caused by natural or man-made factors. We hope analyze interannual variations of green water teleconnections in subsequent research.

In the revision, we added this point in the section Discussion and the revised texts are shown below.

Moreover, the resulting moisture trajectory data only represent the climatologically average moisture trajectories and ET (Li et al., 2023), neglecting the interannual variability in moisture flow trajectory, e.g., those induced by the influence of extreme weather events or ENSO (Zhao and Zhou, 2021). The interannual variations in green water flow may affect DPR and DSR in some provinces. Human adaptation tends to buffer the impacts of interannual variations on the socio-economy through water resource management such as reservoirs, dams, and other infrastructure. Accounting for interannual variations in green water flows and their socio-economic contribution is worth further investigation.

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Comment 2

The paper presents a novel and insightful approach to connect green water flows to their economic value across different provinces in China. The manuscript is well-structured and written. However, there are a few points that could be clarified and improved to enhance the overall impact and clarity of the study.

Response: Thank you for taking your time to review our study and provide feedback and comments. Following the suggestions and comments, we have extensively revised the manuscript and provided a point-to-point response to each comment. The original comments are in **bold** font, our response is in regular font, and the changes in the text are in blue.

1. **The use of the UTrack dataset for processing and tracking the green water flow is commendable. But the uncertainties associated with the input precipitation data (P) in the forward-tracking process need further elaboration.**
    1.1 **It would be good to include the processing scripts for the UTrack dataset and a clearer explanation how you got from the dataset to the data that is used in the already included Python notebook.**
    1.2 **Additionally, this preprint (https://www.researchsquare.com/article/rs-4177311/v1) indicates that the water balance in the UTrack dataset does not appear to be closed, which leads to under- and overestimations of P and ET in either tracking direction. While this may be difficult to solve in the scope of this study, its implications should be discussed and made aware of. How could such uncertainties be addressed and how do they influence the results of this study?**

Response: Thank you for the comments.

1. Uncertainties associated with the input precipitation data (P) affect the precipitation contribution and precipitation recycling ratio.

The revised texts in section Discussion are shown below:

First, ET and precipitation datasets driving the UTrack model affect the tracked trajectories and magnitude of moisture flow. The resulting moisture trajectory is expressed as the fraction of ET to precipitation, and the exact amount of moisture is restored by the ET and precipitation datasets chosen by users. Different ET and precipitation datasets could lead to different precipitation contributions and PRR (Li et al., 2023). We used the ERA5 dataset to keep consistent with the original UTrack model. It is noted that the non-closure of the moisture balance from ERA5 (De Petrillo et al., 2024) and simplifications and assumptions introduced in the moisture tracking model also add uncertainty in the moisture tracking (Tuinenburg and Staal, 2020).

1.1 We will share all the processing scripts for the UTrack dataset and our analysis before publication of the paper.

The link has been added in the revision and is shown below.

The Python codes and data used in this study are available at GitHub (https://github.com/sangshan-ss/GW-China).

1.2 The preprint by De Petrillo.et al indicates deviations between the tracked evaporation (ET) and precipitation (P) volumes at the country/ocean scale, because of the unclosed water balance by ERA5. The non-closure of water balance leads to more uncertainties in capturing moisture tracking. This preprint used the Iterative Proportional Fitting (IPF) procedure to adjust the tracked moisture flow matrices to ensure that the total evaporation and precipitation volumes match the reanalysis data at the country/ocean scale.

We estimated the ratio of P in sink province originating from ET of different source province, and then used the observed provincial P to estimate the P contribution from each province. This practice ensures that provincial P is 100% decomposed into different sources, avoiding the estimation bias of sink precipitation due to unclosed water balance by ET and P data. This point was added in the revision Section Method, shown as below.

We quantified interprovincial moisture flows and their precipitation contribution following the workflow described in Fig. A1. At each sink grid, the ET to precipitation fractions from the moisture trajectory datasets were multiplied by ERA5 evapotranspiration (ET) to obtain monthly precipitation contribution by moisture from its source grids. Repeating the calculation for all grids within a sink province and summing them up yielded the precipitation in the sink province contributed by each source grid (Fig. A1 Step 1). Next, we employed zonal statistics to sum up precipitation in the sink province contributed by grids of each source province, and the precipitation contribution was converted to relative values, i.e., the fraction of precipitation in sink province *j* originating from green water of a source province *i* (denoted as W_{ij}) rather than absolute contribution to reduce the uncertainty in the latter (Fig. A1 Step 2). The fractions W_{ij} multiplied by the observed precipitation of the sink province restore the absolute precipitation contribution. This practice ensures that provincial precipitation is fully decomposed into different sources, avoiding the estimation bias of sink precipitation due to unclosed water balance by ET and precipitation data (De Petrillo et al., 2024). Finally, the interprovincial green water flows in China were derived after estimating each province individually.

2. While the paper shows a novel approach of linking green water flows to economic values, the connection between green water and socio-economic outcomes needs more clarity.

2.1 Green water appears to be treated similarly to blue water under the assumption that all green water flows can be used by humans and directly transferred into an economic value. But large parts of the flows probably remain inaccessible for direct human use and are rather important for indirect ecosystem services, and the stability of the carbon and hydrologic cycle.

2.2 More clarity is needed to understand how the link between the green water flows and the socio-economic values are made. This is the novel part of this paper and would benefit from making this connection clearer. For instance, sections 3.1 and 3.2 present results which aren't really novel but rather an exploration under a different geographical lens. Section 3.3 presents the novel results of this study and hence, by streamlining 3.1 and 3.2 space could be made to focus and expand on the connection between green water and socio-economic values in China.

Response: Thank you for the comments.

2. We apologize for the confusion regarding the introduction about the connections between green water and socio-economic values.

The tele-connection of green water and socio-economic value is depicted as cascade: green water forms precipitation, then precipitation recharges water resource, which then sustains economic activities, human livelihood and crop growth. So we used the water resource volume, economic output (GDP), population and food production, the four variables, to estimate the green water contribution.

In the revision, we clarify these in section 2.2 and Figure 1. Please see the revised texts and figure below.

Green water from upwind source provinces flows and precipitates downwind to recharge water resources, and therefore sustains socio-economic activities in sink provinces, as depicted in Fig. 1. Consequently, precipitation, water resources, and socio-economic factors such as economic activities, human livelihood, and crop production in sink provinces rely on green water exported from source provinces. Changes in green water may affect water resource volume, and then impact economic activities, livelihood, and crop production through water supply. We chose water resources volume, economic output (measured by GDP), population, and food production as the four socio-economic indictors that are tightly related to water resources to evaluate the socio-economic contributions of green water.

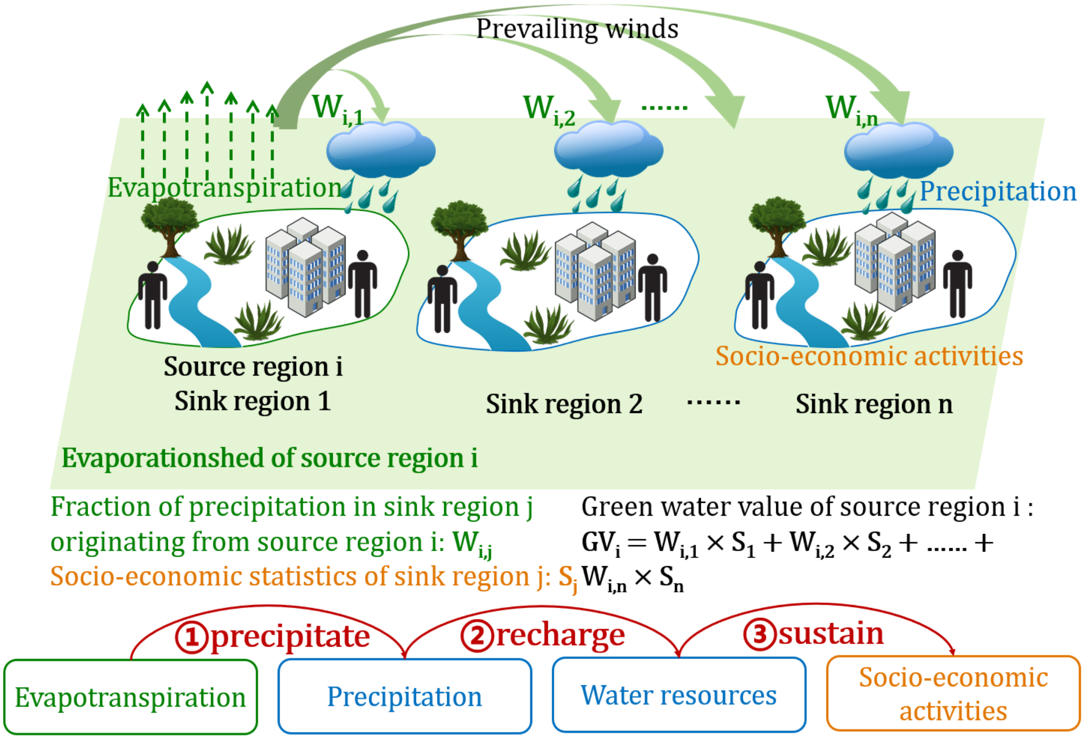

Figure 1. A conceptual diagram depicts the teleconnection of green water flows and their socio-economic contributions in a cascade manner. Evapotranspiration (green dotted arrows) from source region *i* flows downwind with prevailing winds (green thick arrows) and precipitates in sink region *n*, which recharges water sources and sustains socio-economic activities in sink regions.

2.1 We totally agree with that large parts of green water flows probably remain inaccessible for direct human use. Only the water resources generated from precipitation and consumed by human activities sustains the socio-economy. We used the ratio of water resources formed by precipitation (P) in the calculation of green water value. Since this ratio can be eliminated during the calculation process, Equation (1) is simplified and does not show the ratio involved in the calculation. The process of simplification is below. We take the GDP value of ET in one province as an example:

$$\begin{aligned} &\mathit{water\ resouces\ value\ of\ green\ water} \\ &\quad = \frac{\mathit{water\ resources}}{\cancel{P}} \times \cancel{P} \\ &\quad \times \mathit{green\ water\ forming\ P\ fraction} \\ &\quad = \mathit{water\ resources} \times \mathit{green\ water\ forming\ P\ fraction} \end{aligned}$$

$$\begin{aligned} &\mathit{GDP\ value\ of\ green\ water} \\ &\quad = \frac{\mathit{water\ resources\ value\ of\ green\ water}}{\mathit{water\ resources}} \times \mathit{GDP\ value} \\ &\quad = \frac{\cancel{\mathit{water\ resources}} \times \mathit{green\ water\ forming\ P\ fraction}}{\cancel{\mathit{water\ resources}}} \\ &\quad \times \mathit{GDP\ vlalue} \\ &\quad = \mathit{green\ water\ forming\ P\ fraction} \times \mathit{GDP\ value} \end{aligned}$$

This research assume that all the used water resources are from precipitation generated by green water. This point was added in the Discussion and revised texts are shown below:

Secondly, the socio-economic value assessment of green water in this study only considers green water flows within China, excluding flows moving abroad and to the ocean that may embody socio-economic value beyond the territory of mainland China. We mainly attribute socio-economic values to green water and generated precipitation because precipitation is the ultimate water source for recharging surface and groundwater of a region. Strictly speaking, such attribution needs to be more precise because socio-economy also utilizes streamflow from upstream areas, which deserve separate attention.

In addition, not all water resources replenished by green water-induced precipitation are accessible for human activities since part of them is used by the natural ecosystem (Keys et al., 2019). Therefore, it is necessary to distinguish water sources and consumption to account green water values more accurately. Despite the selected socio-economic indicators closely linked to water resources, green water flows' socio-economic contribution can manifest in other aspects such as livestock production and irrigated agriculture. In future studies, the dynamic linkage between green water, water resources and economic development can be assessed annually by using a long-term moisture tracking dataset with a separation of water sources consumed by socio-economy (surface and groundwater).

2.2 Sections 3.1 and 3.2 show the results of interprovincial green water transfer. Many studies have analyzed the pattern of moisture recycling in China from amphoteric and hydrological sciences, they identified moisture source and sinks at the grid (Zhang et al., 2023), basin (Wang et al., 2023) and ecological regional scale (Xie et al., 2024). These studies present a clear understanding of the large-scale spatial pattern of moisture circulation. Few studies focus on the moisture recycling analysis at the administrative district scale, which is important for the water management. Therefore, this study promotes the application of moisture recycling at the water resources management scale, which is also important for research outside the field of atmospheric science.

Sections 3.1 and 3.2 can help water resources managers understand the moisture recycling. The network of interprovincial moisture recycling is the basis of the socio-economic contribution of green water in each province.

In the revision, we streamlined 3.1 and 3.2, and merged them. The revised texts are shown below.

3.1 The interprovincial green water flows in China and their directions

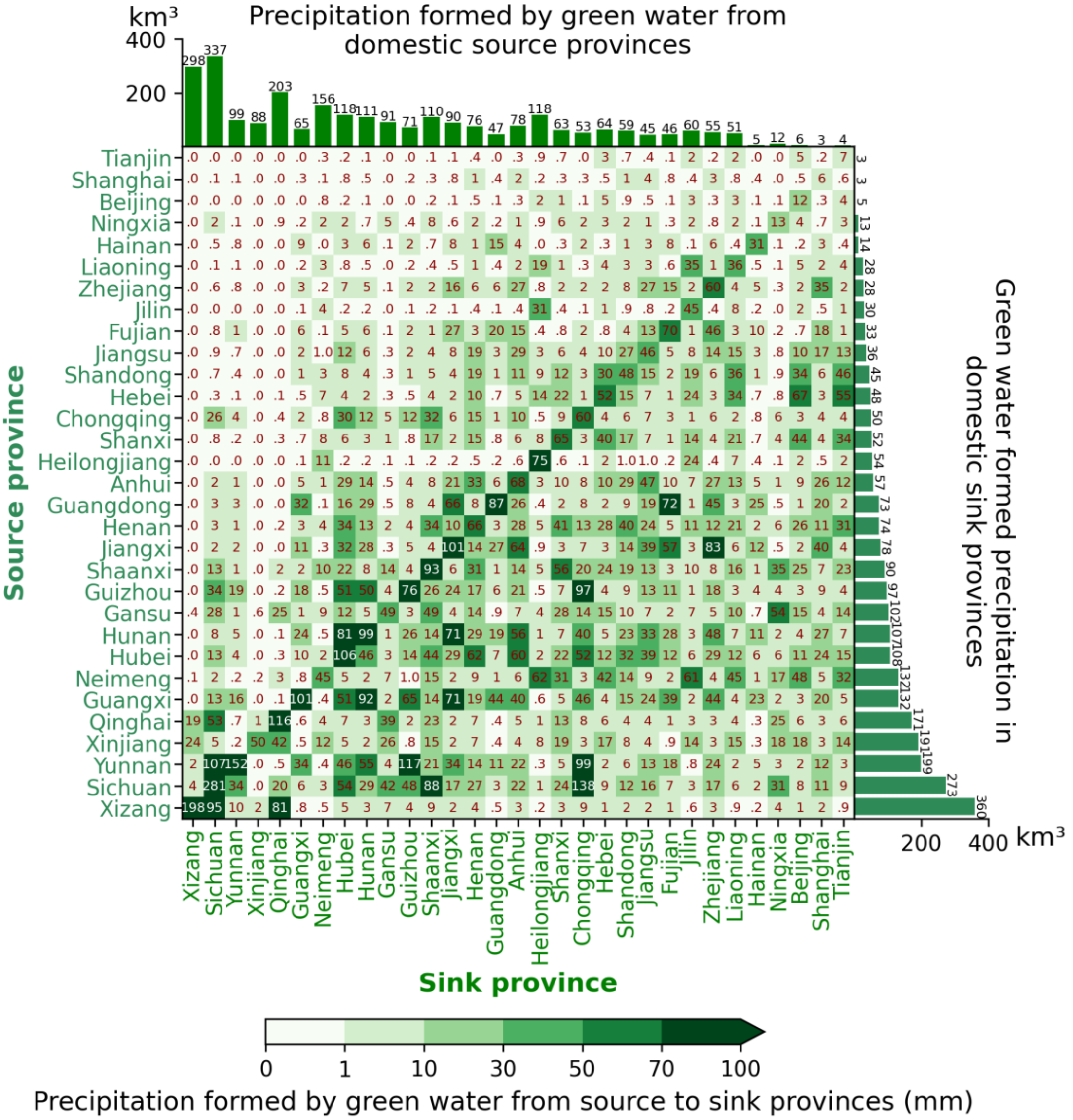

Figure 2. Interprovincial green water flows in China. The heat map denotes precipitation in sink province generated by green water from a source province (mm). The right bar shows domestic precipitation (km^3) formed by green water from each source province. The top bar shows precipitation in each sink province formed by green water from domestic source provinces (km^3).

Green water exported from a source province forms precipitation in different sink provinces in China, and precipitation in a sink province originates from green water in different source provinces. Therefore, different provinces in China, acting either as sources or sinks, are interconnected through moisture recycling and established an interprovincial network (Fig. 2).

A large fraction of green water exported from each source province is retained locally to generate precipitation (diagonal cells in Fig. 2). The precipitation recycling ratio (PRR), the ratio of precipitation generated by local green water to total precipitation, reflects how much green water of each source province contributes to its own precipitation (Fig. A2c). Xizang has the highest PRR of 0.345, followed by Qinghai (0.341) and Sichuan (0.297). Besides local recycling, green water predominantly flows and generates more precipitation in neighboring provinces and less in distant provinces. For example, green water from Sichuan forms high precipitation in neighboring provinces such as Chongqing (138 mm), far surpassing other distant sink provinces (< 88 mm).

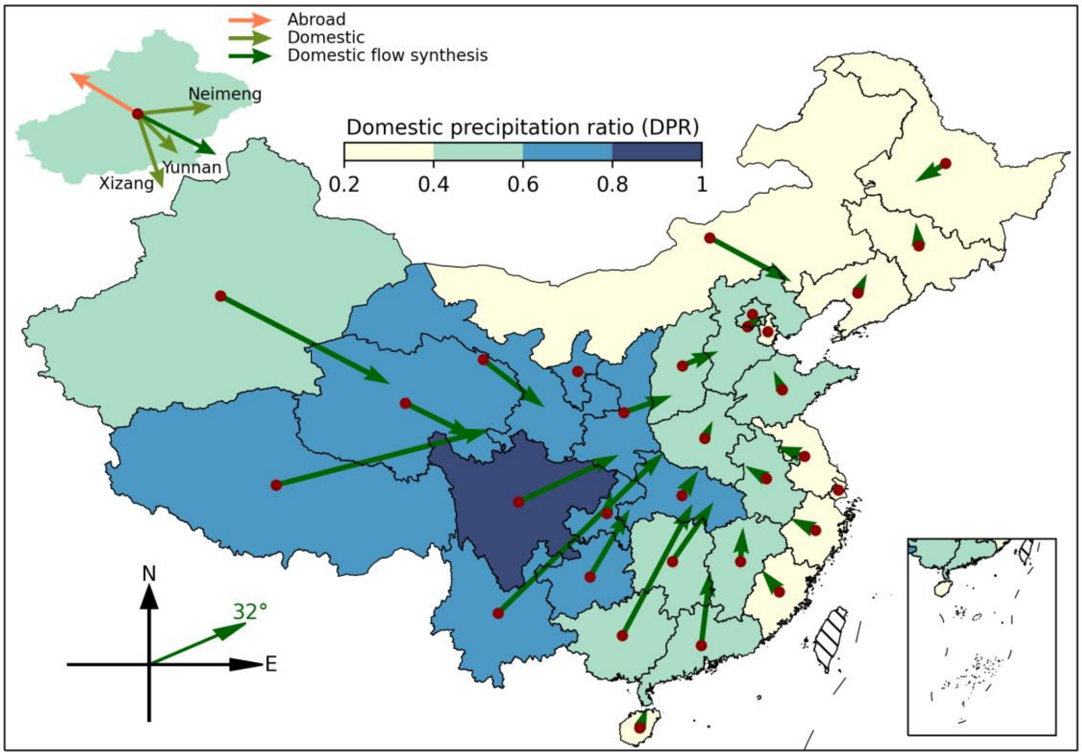

Figure 3. Direction of green water flows from each source province in China. Green arrows indicate the average direction of domestic green water flows, denoted as a vector starting from a source (the geometric center in red points) to sink provinces and with its length representing the amount of precipitation formed by green water. The face colors on the map represent fractions of green water formed precipitation within China of each source province (DPR). The upper left corner is a schematic diagram for green water flows from Xinjiang. The lower left corner is the composite flow direction of interprovincial green water of all provinces.

The direction of interprovincial green water flow can be visualized as a composite direction averaging all domestic green water flows from each source province, which are mainly determined by atmospheric wind conditions, source location, and green water volume (Fig. 3). Overall, the average direction of all interprovincial green water flows is at 32° northeastward (32° north off the east direction), suggesting green water within China is transported to the north and east directions owning to combined effects of monsoons and westerly.

Green water exported by source provinces contributes to precipitation both within and outside China. We defined the domestic precipitation ratio (DPR) as the ratio of green water that formed precipitation in China to each province's total green water export to represent their relative importance to China's precipitation (Fig. A2a). Green water from provinces in western and central China mainly flows eastward under the influence of prevailing westerlies, which extend their evaporationsheds eastward to cover a large territory of China and generate more precipitation within China (Fig. 3). For instance, green water from Xizang, the largest exporter in China, produces the largest domestic precipitation (360 km^3) (right bar on Fig 2) with a high DPR of 0.74, contributing to precipitation in other 30 provinces with varying extents (0.2 to 95 mm). Similarly, the green water from southern provinces is affected by the Indian Ocean Monsoon (southwest monsoon), which drives green water flowing northeastward. With a substantial volume of green water, these southern provinces contribute significantly to domestic precipitation. In contrast, green water from eastern coastal or northwest border provinces goes to the northwest primarily attributed to the East Asian Monsoon (southeast monsoon) (Cai et al., 2010). As a result, most evaporationsheds laid outside China generate less domestic precipitation but more outside the country, resulting in a lower DPR, such as Fujian (DPR 0.31) and Heilongjiang (DPR 0.23). The northern provinces are influenced by westerly winds and winter monsoon from Siberia (Sun et al., 2012), causing predominantly southeastward flow of green water. However, evaporationsheds of these provinces mainly cover the Pacific Ocean, resulting in a relatively low DPR despite their substantial volume of exported green water. While some inland provinces have a high DPR because their evaporationsheds overlap with mainland China, the low green water volume (Fig. A4) limits their domestic precipitation contribution (e.g., Gansu and Ningxia with DPR of 0.72 and 0.66, respectively).

Furthermore, precipitation in sink provinces originates from both domestic and foreign green water sources. Sichuan (337 km^3), Xizang (298 km^3), and Qinghai (203 km^3) are the top 3 provinces importing the largest volume of green water from domestic sources due to the large ET from themselves and neighboring provinces (top bar of Fig 2). To quantify the relative importance of domestic sources, we defined the domestic source ratio (DSR) in each province as the sum of precipitation contribution from domestic sources divided by total precipitation (Fig. A2 (b)). DSR is related to each province's precipitationshed (i.e., upwind region contributing evaporation to a specific location's precipitation) (Keys et al., 2014) and the included domestic green water exporters. The highest DSR found in Qinghai (0.86) and Ningxia (0.82) is because their precipitationsheds include large domestic green water exporters like Xinjiang and Xizang, which supply considerable green water traveling eastward. Conversely, Hainan (0.07) and Guangdong (0.14) in coastal areas have lower DSR because their precipitationsheds are primarily located in oceans and other countries due to the influence of the summer monsoon (Cai et al., 2010).

Reference:

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Zhang, B., Gao, H., and Wei, J.: Identifying potential hotspots for atmospheric water resource management and source-sink analysis, CSB, 68, 2678–2689, https://doi.org/10.1360/TB-2022-1275, 2023.

Comment 3

The present manuscript provides an emblematic example of integrating green water flows at a sub-national level in water management strategies. It expands on recent studies that highlighted the socio-economic value of green water teleconnections. The topic is suitable for publication and of interest to the readership of EGUsphere.

Response: Thank you for taking your time to review our study and provide feedback and comments. Following the suggestions and comments, we have extensively revised the manuscript and provided a point-to-point response to each comment. The original comments are in **bold** font, our response is in regular font, and the changes in the text are in blue.

I would recommend the publication of this paper after major revisions. In the following, there are some comments that the authors may want to consider when revising their manuscript. These revisions should enhance the manuscript's clarity and depth.

Specific comments:

Abstract:

Lines 15-16: Pay attention to verb consistency for better clarity and flow.

Response: Thank you for the comments.

We modified this part to be more specific, and the revised texts are shown below:

Green water (terrestrial evapotranspiration) flows from source regions, precipitates downwind via moisture recycling, recharges water resources, and sustains the socio-economy in sink regions.

Lines 19-21: The dataset used for the analysis is not well introduced or explained. Provide a more detailed and concise explanation of the data used.

Response: Thank you for the comments.

In the revision, we revised the sentence to include more information. The revised texts are shown below:

This study used a climatology mean moisture trajectory dataset produced by the Utrack model for 2008-2017 to quantify interprovincial green water flows in China and their socio-economic contributions.

And in Section 2.1, we added a more detailed introduction about the UTrack moisture tracking dataset. The revised texts are shown below:

This study used the moisture trajectory dataset generated by the Lagrangian moisture tracking model "UTrack-atmospheric-moisture" driven by ERA5 reanalysis data. The model is the state-of-the-art moisture tracking model, producing more detailed evaporation footprints due to the high spatial resolution and reduced unnecessary complexity (Tuinenburg and Staal, 2020). The dataset provides monthly mean moisture flows at the global scale with a spatial resolution of 0.5° for 2008-2017, expressed as the fractions of evaporation from a source grid allocated to precipitation at a sink grid (Tuinenburg et al., 2020). It has been widely used in moisture recycling research with various spatial scales, such as precipitation source of the grid (Staal et al., 2023; Wei et al., 2024; Zhang et al., 2023) and basin scale (Wang et al., 2023), and moisture transport between nations (Rockström et al., 2023). The moisture trajectory dataset was used in conjunction with the multi-year monthly mean ET of 2008–2017 from the ERA5 reanalysis dataset to estimate precipitation in a sink grid originating from a source grid.

Line 22: Include the specific value of the average self-recycling ratio.

Response: Thank you for the comments.

In the revision, we added the range of self-recycling ratio, and revised texts are shown below:

Despite self-recycling (ranging from 0.6% to 35%), green water mainly forms precipitation in neighboring provinces, with average interprovincial flow directions from west to east and south to north.

Lines 32-35: This passage is unclear. Consider rephrasing and supporting it with specific results.

Response: Thank you for the comments.

In the revision, we rephrased this passage, and the revised texts are shown below:

Overall, the embodied socio-economic values of green water flow increase from source to sink provinces, suggesting that green water from less developed provinces effectively supports the higher socio-economic status of developed provinces.

Introduction:

Line 45: Consider adding additional references for the average global terrestrial moisture recycling ratio. Rockström (2023) cites Tuinenburg (2020), they are essentially the same reference.

Response: Thank you for the comments.

In the revision, we changed the references, and the revised texts are shown below:

Terrestrial evapotranspiration (i.e., green water) (Falkenmark and Rockström, 2006), which includes evaporation and transpiration from land and vegetation, contributes to over half of the global precipitation on land (van der Ent et al., 2010; Theeuwen et al., 2023; Tuinenburg et al., 2020).

Lines 60-61: Clarify the period of reference for the change mentioned. Specify when the change occurred and add recent references for support.

Response: Thank you for the comments.

In the revision, the period of reference was clarified, and the revised texts are shown below:

Due to upstream water withdrawal and dams, global total blue water flow into oceans and internal sinks decreased by 3.5% in 2002 compared to 1961–1990 (Döll et al., 2009).

Lines 99-103: This section is unclear. Rephrase for better clarity.

Response: Thank you for the comments.

In the revision, we rephrased this passage and revised texts are shown below:

Recent studies analyzed the large-spatial pattern of moisture recycling in China at the grid (Zhang et al., 2023), river basin (Wang et al., 2023), and ecological regions scales (Xie et al., 2024), or for specific regions (Pranindita et al., 2022; Zhang et al., 2024). However, green water flows from different regions are interlinked and become sources and sinks of each other. Such green water transfer at a sub-national scale effectively forms an interconnected green water flow network. It highlights the mutual dependency of green water and its socio-economic contributions, especially for large countries like China.

General Comments:

The Introduction could benefit from clearer explanations of certain passages. Include a characterization of China's moisture recycling patterns, atmospheric

circulation, and climatic seasonality to frame the phenomenon of moisture flows. For instance, compare the importance of moisture recycling in China to other regions globally.

Response: Thank you for the comments.

In the revision, we added the introduction about China's moisture recycling patterns, atmospheric circulation, and climatic seasonality. The revised texts are shown below:

The general spatial and seasonal patterns of moisture flows in China are determined by regional atmospheric circulation systems, including prevailing westerly winds (from the west toward the east) in most of China between 30° and 60° (Bridges et al., 2023), the East Asian monsoon in eastern China, and India monsoon in southwestern China. In summer, the East Asian and Indian monsoons supply moisture for precipitation in eastern and southwestern China (Tian and Fan, 2013). In winter, the East Asian monsoon drives northwesterly moisture transport across much of China and generates precipitation (Wu and Wang, 2002).

Discuss the socio-economic background of the Chinese provinces involved. Highlight key socio-economic sectors and societal issues/characteristics of these regions.

Response: Thank you for the comments.

In the revision, we added the socio-economic background of the Chinese provinces. The revised texts are shown below:

Few studies focus on green water flows at the administrative district scale, which is important for water management. Furthermore, the substantial regional disparities in socio-economic development add complexity to understanding the socio-economic contributions of green water among Chinese provinces. The western provinces with a weak economic status and sparse populations are abundant in water resources (Ya-Feng et al., 2020). In contrast, the economically developed and densely populated eastern provinces suffer from water scarcity (Varis and Vakkilainen, 2001). Therefore, quantifying interprovincial green water flows and evaluating the embedded socio-economic values offer new perspectives for optimizing water resource utilization and mitigating the imbalance in regional socio-economic development.

Explain why analyzing green water flows at an inter-regional scale is significant, both generally and specifically for China.

Response: Thank you for the comments.

Although many research analyzed the spatial pattern of moisture recycling in China from amphoteric and hydrological sciences, they identified moisture source and sinks at the grid (Zhang et al., 2023), river basins (Wang et al., 2023), and ecological regions scale (Xie et al., 2024). There is a clear understanding of the large-scale spatial pattern of moisture circulation, few researches focus on quantify moisture recycling at the administrative district scales, which is important for the water management. Therefore, this study applies moisture recycling techniques to inform green water transfer at among provinces, which is previously less known but important for regional water resources management.

In the revision, we added the explanation, the revised texts are shown below.

Recent studies analyzed the large-spatial pattern of moisture recycling in China at the grid (Zhang et al., 2023), river basin (Wang et al., 2023), and ecological regions scales (Xie et al., 2024), or for specific regions (Pranindita et al., 2022; Zhang et al., 2024). However, green water flows from different regions are interlinked and become sources and sinks of each other. Such green water transfer at a sub-national scale effectively forms an interconnected green water flow network. It highlights the mutual dependency of green water and its socio-economic contributions, especially for large countries like China. Few studies focus on green water flows at the administrative district scale, which is important for water management. Furthermore, the substantial regional disparities in socio-economic development add complexity to understanding the socio-economic contributions of green water among Chinese provinces. The western provinces with a weak economic status and sparse populations are abundant in water resources (Ya-Feng et al., 2020). In contrast, the economically developed and densely populated eastern provinces suffer from water scarcity (Varis and Vakkilainen, 2001). Therefore, quantifying interprovincial green water flows and evaluating the embedded socio-economic values offer new perspectives for optimizing water resource utilization and mitigating the imbalance in regional socio-economic development.

Data and Methods:

General Comment: This section requires substantial improvements.

Structure: Separate the Data and Methods into two subsections. Move Figure 1 to the Methods subsection and provide detailed explanations in the caption.

Response: Thank you for the comments.

In the revision, we separated the Data and Methods into two subsections. And added detailed explanations in the caption of Figure 1. The revised texts are shown below.

2 Data and Methods

2.1 Data

This study used the moisture trajectory dataset generated by the Lagrangian moisture tracking model “UTrack-atmospheric-moisture” driven by ERA5 reanalysis data. The model is the state-of-the-art moisture tracking model, producing more detailed evaporation footprints due to the high spatial resolution and reduced unnecessary complexity (Tuinenburg and Staal, 2020). The dataset provides monthly mean moisture flows at the global scale with a spatial resolution of 0.5° for 2008-2017, expressed as the fractions of evaporation from a source grid allocated to precipitation at a sink grid (Tuinenburg et al., 2020). It has been widely used in moisture recycling research with various spatial scales, such as precipitation source of the grid (Staal et al., 2023; Wei et al., 2024; Zhang et al., 2023) and basin scale (Wang et al., 2023), and moisture transport between nations (Rockström et al., 2023). The moisture trajectory dataset was used in conjunction with the multi-year monthly mean ET of 2008–2017 from the ERA5 reanalysis dataset to estimate precipitation in a sink grid originating from a source grid. The socio-economic statistical data in 2008-2017 from the China Statistical Yearbook were used to estimate the socio-economic values of green water in terms of water resources volume, gross domestic product (GDP), population, and food production for 31 provinces in mainland China, without Hong Kong, Macau, and Taiwan due to the data limitation. GDP was adjusted to price in the year 2020 to eliminate the effects of inflation.

2.2 Quantify green water flows in China

We quantified interprovincial moisture flows and their precipitation contribution following the workflow described in Fig. A1. At each sink grid, the ET to precipitation fractions from the moisture trajectory datasets were multiplied by ERA5 evapotranspiration (ET) to obtain monthly precipitation contribution by moisture from its source grids. Repeating the calculation for all grids within a sink province and summing them up yielded the precipitation in the sink province contributed by each source grid (Fig. A1 Step 1). Next, we employed zonal statistics to sum up precipitation in the sink province contributed by grids of each source province, and the precipitation contribution was converted to relative values, i.e., the fraction of precipitation in sink province j originating from green water of a source province i (denoted as W_{ij}) rather than absolute contribution to reduce the uncertainty in the latter (Fig. A1 Step 2). The fractions W_{ij} multiplied by the observed precipitation of the sink province restore the absolute precipitation contribution. This practice ensures that provincial precipitation is fully decomposed into different sources, avoiding the estimation bias of sink precipitation due to unclosed water balance by ET and precipitation data (De Petrillo et al., 2024). Finally, the interprovincial green water flows in China were derived after estimating each province individually.

The direction of green water flows can be represented by a vector starting from a source to sink province determined by their geometric centers and with its length denoting flow magnitude. Since green water flows have multiple destinations, each flow points to different sink provinces, and even outside of China. For each source province, all of their domestic green water flow vectors can be averaged to a composite to represent their net direction and magnitude, which are mainly determined by atmospheric wind conditions, source location and green water volume.

2.3 Quantify socio-economic values embodied in green water

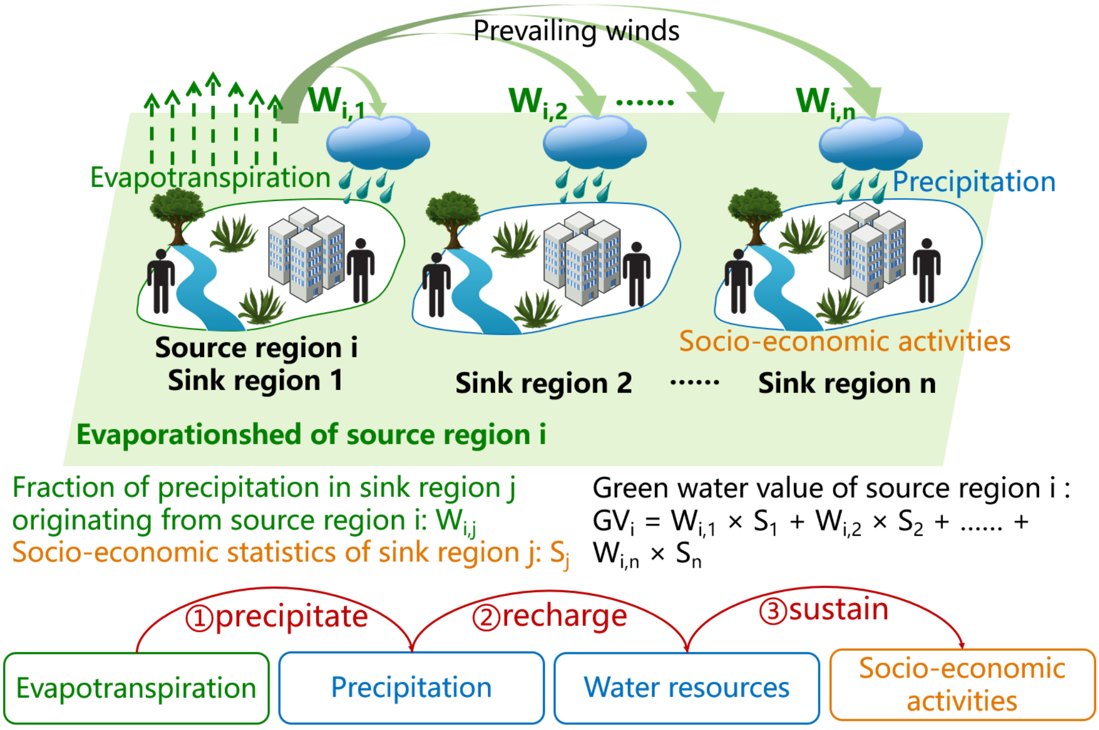

Figure 1. A conceptual diagram depicts the teleconnection of green water flows and their socio-economic contributions in a cascade manner. Evapotranspiration (green dotted arrows) from source region *i* flows downwind with prevailing winds (green thick arrows) and precipitates in sink region *n*, which recharges water sources and sustains socio-economic activities in sink regions.

Green water from upwind source provinces flows and precipitates downwind to recharge water resources, and therefore sustains socio-economic activities in sink provinces, as depicted in Fig. 1. Consequently, precipitation, water resources, and socio-economic factors such as economic activities, human livelihood, and crop production in sink provinces rely on green water exported from source provinces. Changes in green water may affect water resource volume, and then impact economic activities, livelihood, and crop production through water supply. We chose water resources volume, economic output (measured by GDP), population, and food production as the four socio-economic indictors that are tightly related to water resources to evaluate the socio-economic contributions of green water.

If we assume all socio-economic activities in sink province j are sustained by precipitation which constitutes water resources and recharges groundwater, socio-economic statistics of sink province j can be partitioned to source provinces by their share of precipitation contribution (W_{ij}). Therefore, multiplying socio-economic statistics in sink province j (S_j) by W_{ij} yielded the socio-economic value of green water from source province i. The total socio-economic value of green water of source province i (GV_i) can be obtained by summing its contributions to all sink provinces (Fig. 1), as equation (1):

$$GV_i = \sum_{j=1}^{n} (W_{i,j} \times S_j), \tag{1}$$

where S_j is the average socio-economic value of 2008-2017 (i.e., water resources volume (km^3), GDP (in unit of CNY, 1 CNY = 0.14 USD), population (persons), and food production (ton)) at sink province j, n is the number of sink provinces.

Due to the different socio-economic development statuses, the same amount of green water may produce different socio-economic values between source and sink provinces. This means green water flow also involves changes in embodied socio-economic value from source to sink provinces. We used water productivity in the source province (WP_i) to calculate the socio-economic values of its exported green water in the counterfactual scenario when it was all consumed in the source province without interprovincial transfer (GV_i') (Eq. 2). The results were compared with the actual green water's socio-economic values (Eq. 1) (namely socio-economic values of exported green water when it is consumed in sink provinces) as:

$$GV_i' = \sum_{j=1}^{n} (W_{i,j} \times WU_j \times WP_i), \tag{2}$$

where WU_j is water use in sink province j, and WP_i is water productivity in source province i. (i.e., economic output, population, and food production per unit water use). The changes in the socio-economic value of green water flow (ΔGV_i) from source province i to its sink provinces can be estimated by Eq. 3.

$$\Delta GV_i = GV_i - GV_i' \tag{3}$$

$\sum_{i=1}^{n} \Delta \mathrm{GV}_i$ is the net change in socio-economic values of all interprovincial green water flows in China.

Figure 1: The caption should be more detailed to enhance understanding.

Response: Thank you for the comments.

In the revision, we added detailed explanations in the caption of Figure 1.

The revised figure and its caption are shown below:

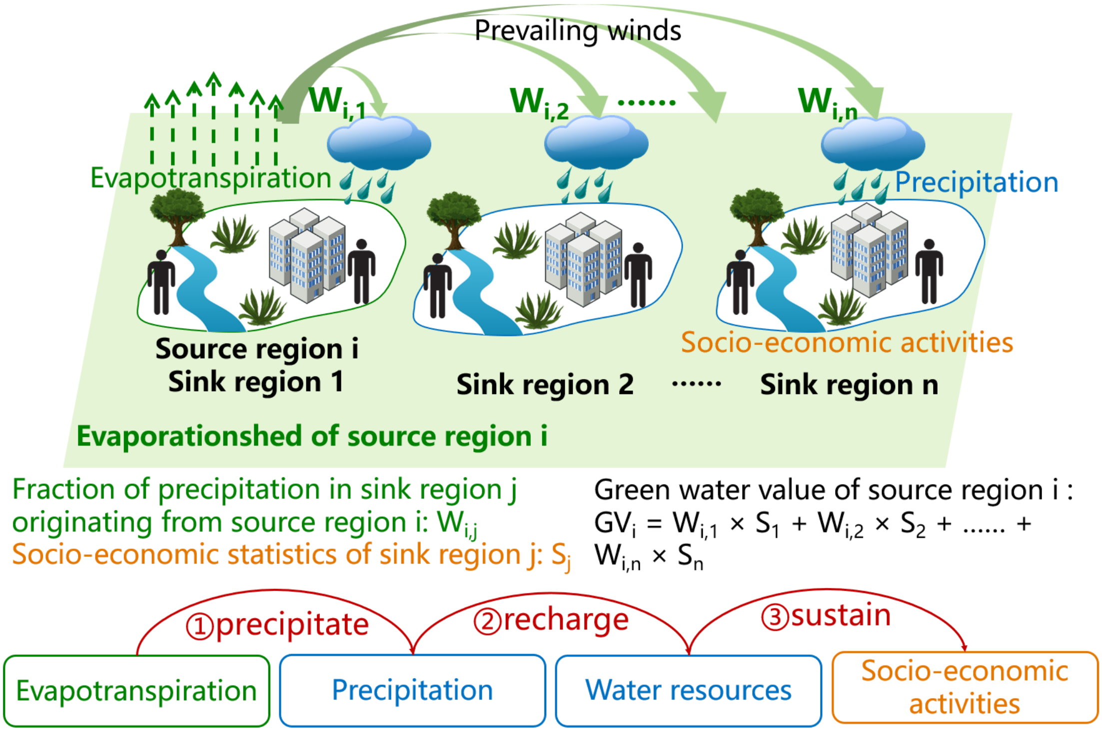

Figure 1. A conceptual diagram depicts the teleconnection of green water flows and their socio-economic contributions in a cascade manner. Evapotranspiration (green dotted arrows) from source region i flows downwind with prevailing winds (green thick arrows) and precipitates in sink region n, which recharges water sources and sustains socio-economic activities in sink regions.

Lines 127-138: Provide a more detailed explanation of the reconstruction of flows from the UTrack dataset. Clarify the processing with zonal statistics, possibly using equations or schemes for better comprehension.

Response: Thank you for the comments.

In the revision, we added detailed explanations of the reconstruction of flows from the UTrack dataset in Section 2.2 and Figure A1. The revised texts and figure are shown below:

We quantified interprovincial moisture flows and their precipitation contribution following the workflow described in Fig. A1. At each sink grid, the ET to precipitation fractions from the moisture trajectory datasets were multiplied by ERA5 evapotranspiration (ET) to obtain monthly precipitation contribution by moisture from its source grids. Repeating the calculation for all grids within a sink province and summing them up yielded the precipitation in the sink province contributed by each source grid (Fig. A1 Step 1). Next, we employed zonal statistics to sum up precipitation in the sink province contributed by grids of each source province, and the precipitation contribution was converted to relative values, i.e., the fraction of precipitation in sink province *j* originating from green water of a source province *i* (denoted as W_{ij}) rather than absolute contribution to reduce the uncertainty in the latter (Fig. A1 Step 2). The fractions W_{ij} multiplied by the observed precipitation of the sink province restore the absolute precipitation contribution. This practice ensures that provincial precipitation is fully decomposed into different sources, avoiding the estimation bias of sink precipitation due to unclosed water balance by ET and precipitation data (De Petrillo et al., 2024). Finally, the interprovincial green water flows in China were derived after estimating each province individually.

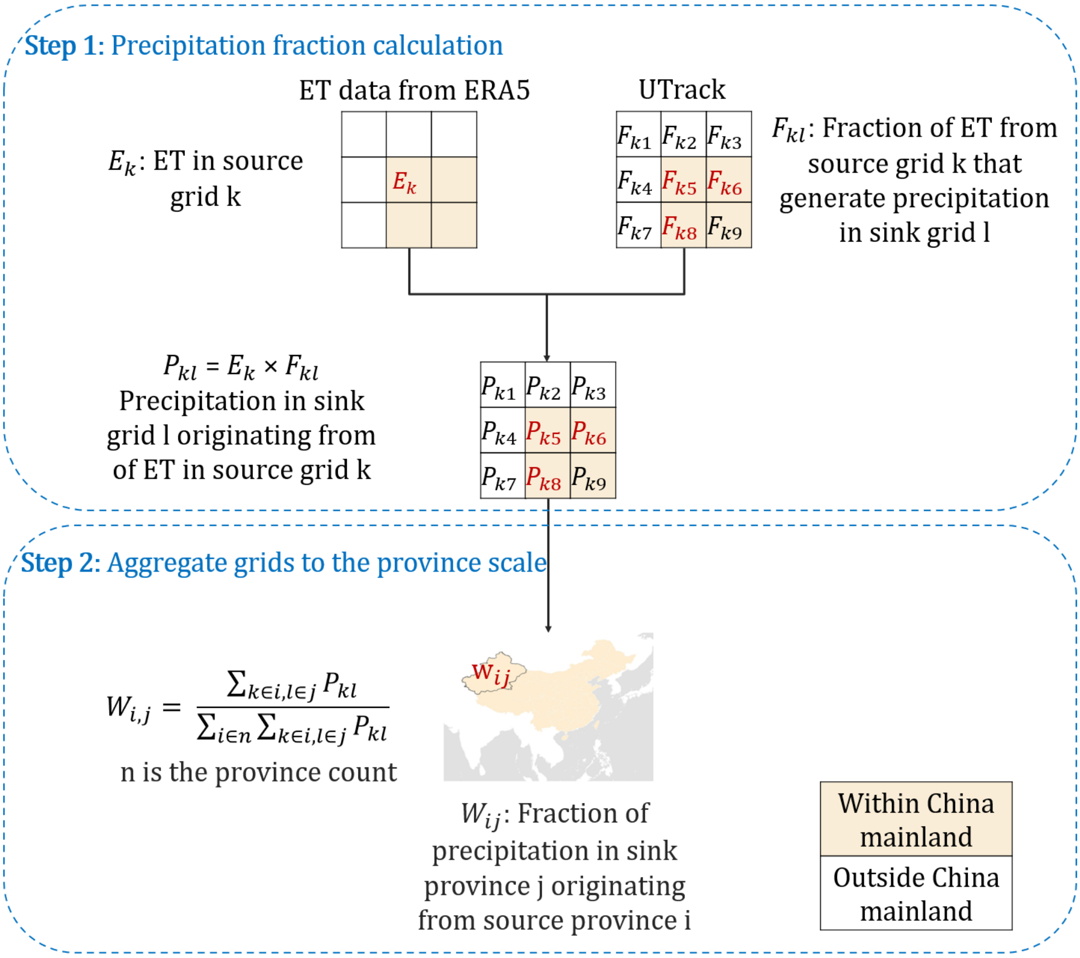

Figure A1. Workflow of estimating green water flow. Step 1: calculate the precipitation in sink grids originating from ET in source grids. Step 2: calculate the fraction of precipitation in sink provinces originating from source provinces.

Socio-economic Analysis: Since this is the core of the study, it needs a more in-depth analysis. Explain the significance of green water flows for the variables considered. How do they contribute to the services these variables represent?

Response: Thank you for the comments.

In the revision, we added the explanation of green water flows' significance. The revised texts are shown below:

Consequently, precipitation, water resources, and socio-economic factors such as economic activities, human livelihood, and crop production in sink provinces rely on green water exported from source provinces. Changes in green water may affect water resource volume, and then impact economic activities, livelihood, and crop production through water supply. We chose water resources volume, economic output (measured by GDP), population, and food production as the four socio-economic indictors that are tightly related to water resources to evaluate the socio-economic contributions of green water.

Equation 1:

Consider incorporating the areal extension of the provinces. Using population density instead of population, and expressing surface water resources per unit area, would be more appropriate. Similarly, express food production per area rather than gross food production. Use GDP per capita (GDP/P) instead of gross GDP.

Response: Thank you for the comments.

The land area and population of source and sink provinces differ, when using per-unit measures, the socio-economic value of green water is affected by the denominators of the indicators for both the source and sink provinces, making the results difficult to interpret. Alternatively, per-unit measures reflect the different characteristics between the source and sink regions, such as the green water flowing from economically less developed to developed provinces indicated by per capita GDP. These results have already been discussed and analyzed in the manuscript in Section Results. Therefore, we chose to use total amounts of socio-economic indicators to calculate the green water value. And those results are shown below:

3.3 Changing socio-economic values of green water flows

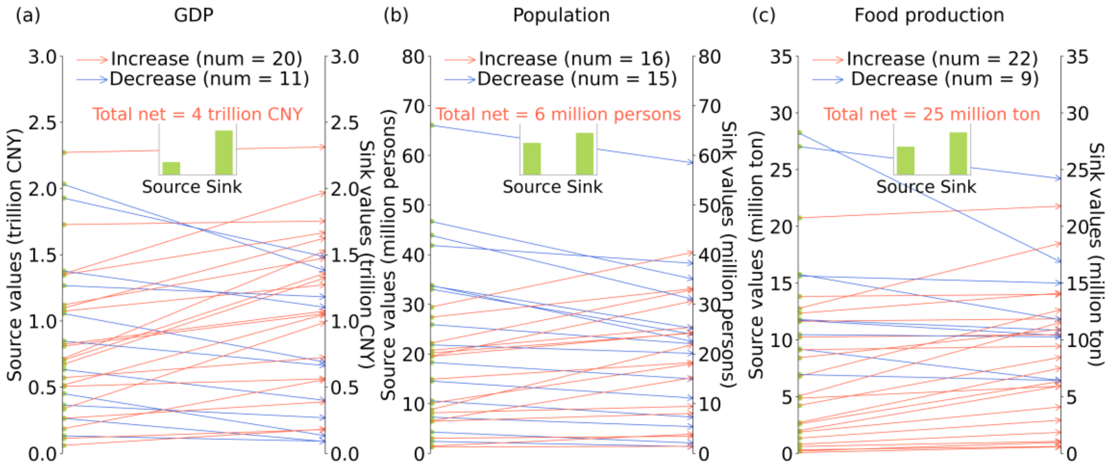

Figure 5. Changes in socio-economic values embodied in green water flow from source to sink provinces for GDP (a), population (b), and food production (c). Thin arrows of different colors represent the socio-economic value increase (in red) or decrease (in blue) from source to sink provinces. Green bars represent the sum socio-economic value in China's 31 provinces.

The substantial socio-economic values embodied in interprovincial green water flows highlight the teleconnection of green water from source provinces and the socio-economy in sink provinces, including economy, population, and food production. Due to different socio-economic statuses, the same amount of consumed water resources, which are recharged by green water, would sustain different socio-economic values between source and sink provinces. Therefore, the socio-economic values embodied in green water flow would change when traveling from source to sink provinces. As shown in Fig. 5, the socio-economic values embodied in green water flow increase from source to sink provinces by 4 trillion CNY for GDP, 6 million for population, and 25 million tons for food production, respectively. The increase in the embodied GDP, population, and food production is observed in 20, 16, and 22 source provinces among a total of 31. This indicates that green water tends to flow from less to more developed provinces, sustaining more economic production, population, and food production per unit of green water. The largest economic output value increases are in Guangxi (+0.83 trillion CNY, 54%). Xinjiang has the most added value in population (+13 million persons, 59%) and food production (+7 million tons, 60%) because their green water flows to more developed provinces (Fig. A5). In contrast, decreased socio-economic values of green water flow are also observed. Shandong, Shaanxi, and Henan have the largest depreciation in green water values for GDP (-0.66 trillion CNY, 48%), population (-13 million persons, 42%), and food production (-12 million tons, 72%) (Fig. A5) because their green water flows to provinces with lower socio-economic values.

The changing socio-economic values of green water flow reflect the regional disparity in socio-economic statuses between source and sink provinces. The exported green water for more than half of the source provinces in China (> 15) has increased socio-economic values when reaching sink provinces. This shows that green water from less developed provinces effectively supports the higher socio-economic status of developed provinces through the interprovincial flow network. Therefore, these provinces are vitally important green water providers to developed areas. This teleconnection of green water and socio-economy substantiates that changing land use in the source provinces that affect evapotranspiration is likely to influence water resources availability and socio-economic development in the sink provinces (Dias et al., 2015; Weng et al., 2018). Hence, it is imperative to account for "invisible" green water flow and its cascade effect in large-scale water resources management.

Address the role of irrigation and irrigation infrastructure in food production to avoid overestimating the contribution of green water flows. Differentiating between irrigated and rainfed productivity could be insightful.

Response: Thank you for the comments.

The irrigation increases ET in source region, then provides more moisture for downwind regions. Simultaneously, most of the water for local irrigation comes from upwind regions. Therefore, it is necessary to distinguish water sources more carefully. In the revision, we added this point in Section Discussion. The revised texts are shown below.

However, the food production data from China Statistical Yearbook is the total food production including both irrigated and rainfed production. It's hard to differentiate the irrigated and rainfed productivity due to the data limitation.

Moreover, the interactions between blue and green water increase the complexity to evaluating green water's socio-economic contribution. For example, the blue water extracted by irrigation increases ET in the source region, providing more moisture for downwind regions (Yang et al., 2019). Simultaneously, most of the blue water for local irrigation comes from the green water of upwind regions (McDermid et al., 2023). In addition, not all water resources replenished by green water-induced precipitation are accessible for human activities since part of them is used by the natural ecosystem (Keys et al., 2019). Therefore, it is necessary to distinguish water sources and consumption to account green water values more accurately.

Include units of measure.

Response: Thank you for the comments.

In the revision, we added units and the revised texts are shown below:

where S_j is the average socio-economic value of 2008-2017 (i.e., water resources volume (km^3), GDP (in unit of CNY, 1 CNY = 0.14 USD), population (persons), and food production (ton)) at sink province j, n is the number of sink provinces.

Equations 2 and 3:

The focus shifts to the consumption patterns of each province. However, Equation 1 deals with food production, which does not equate to food consumption. Food production in one province might be exported elsewhere. Clarify whether the study focuses on production, consumption, or both, and how these dynamics are analyzed.

Response: Thank you for the comments.

We apologize for the confusion regarding the research's focus.

Our research focus on the food production. We used water productivity in source province to calculate socio-economic values of its exported green water in the counterfactual scenario when it was all consumed in source province without interprovincial transfer. The results were compared with the actual green water's socio-economic values (namely socio-economic values of exported green water when it is consumed in sink provinces). What we focused is the difference of food production between the scenario that green water is all consumed in source provinces and actual scenario.

In the revision, we clarified this point more clearly. The revised texts are shown below.

Due to the different socio-economic development statuses, the same amount of green water may produce different socio-economic values between source and sink provinces. This means green water flow also involves changes in embodied socio-economic value from source to sink provinces. We used water productivity in the source province (WP_i) to calculate the socio-economic values of its exported green water in the counterfactual scenario when it was all consumed in the source province without interprovincial transfer (GV_i') (Eq. 2). The results were compared with the actual green water's socio-economic values (Eq. 1) (namely socio-economic values of exported green water when it is consumed in sink provinces) as:

$$GV_i' = \sum_{j=1}^{n} (W_{i,j} \times WU_j \times WP_i), \tag{2}$$

where WU_j is water use in sink province j, and WP_i is water productivity in source province i. (i.e., economic output, population, and food production per unit water use).

General comment: Consider revising Equations 1,2 and 3 to enhance the rigor of the analysis.

Results:

Section 3.1:

Figure 2: The figure has great potential but needs improvements.

Increase its size for better readability of numbers and histograms.

Clarify the label of the right bar in the figure, caption, and text. Consider rephrasing for better understanding.

Response: Thank you for the comments.

In the revision, we improved Figure 2 to increase its readability. The revised figure is shown below:

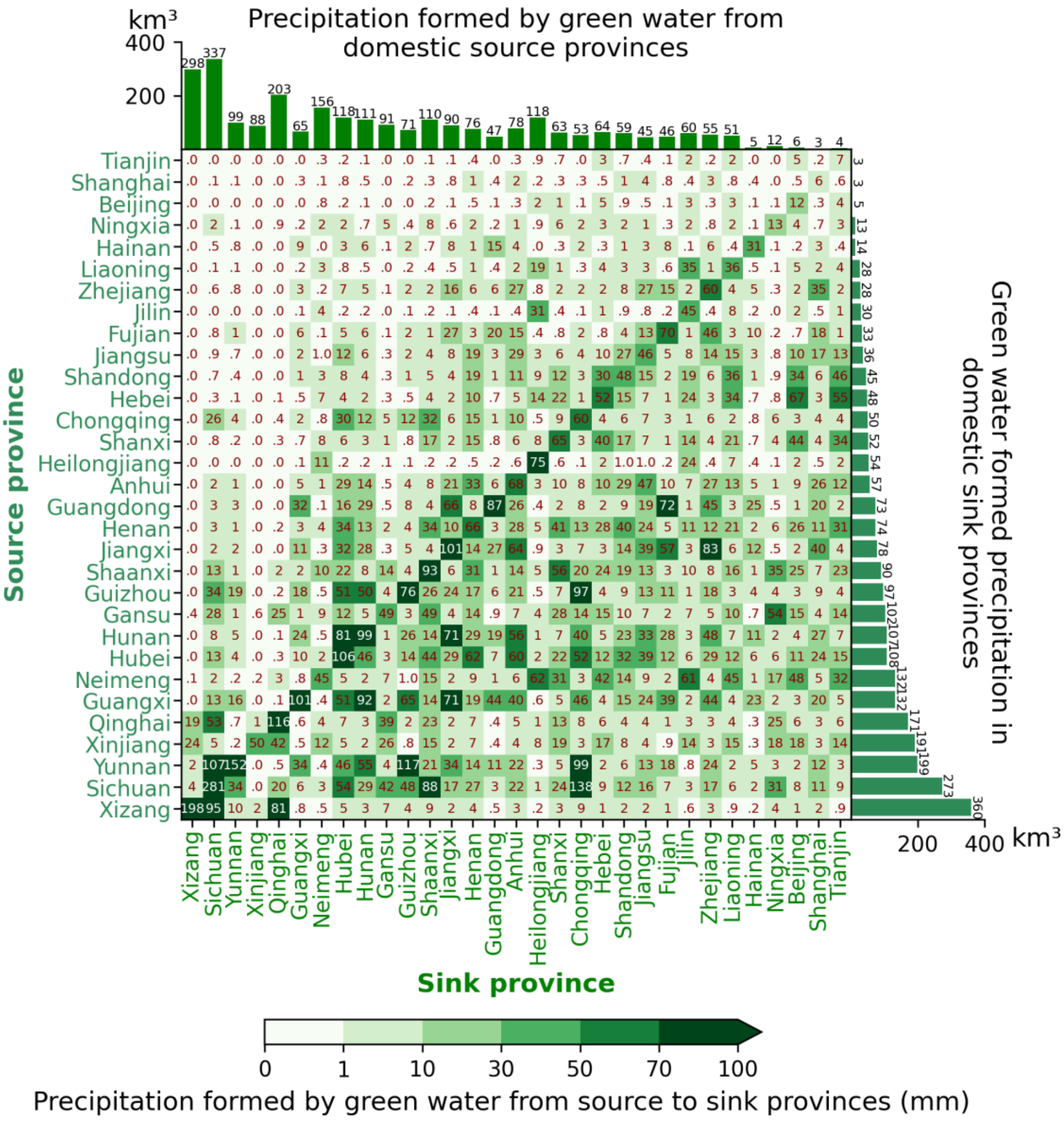

Figure 2. Interprovincial green water flows in China. The heat map denotes precipitation in sink province generated by green water from a source province (mm). The right bar shows domestic precipitation (km^3) formed by green water from each source province. The top bar shows precipitation in each sink province formed by green water from domestic source provinces (km^3).

Lines 195-237: The discussion on PRR, DPR, and DSR contains a lot of information that is difficult to visualize. Consider creating a figure to represent these results to help the discussion of socio-economic implications.

Response: Thank you for the comments.

The information of PRR, DPR, and DSR in each province has shown in Figure A3 (Appendix Figure 3).

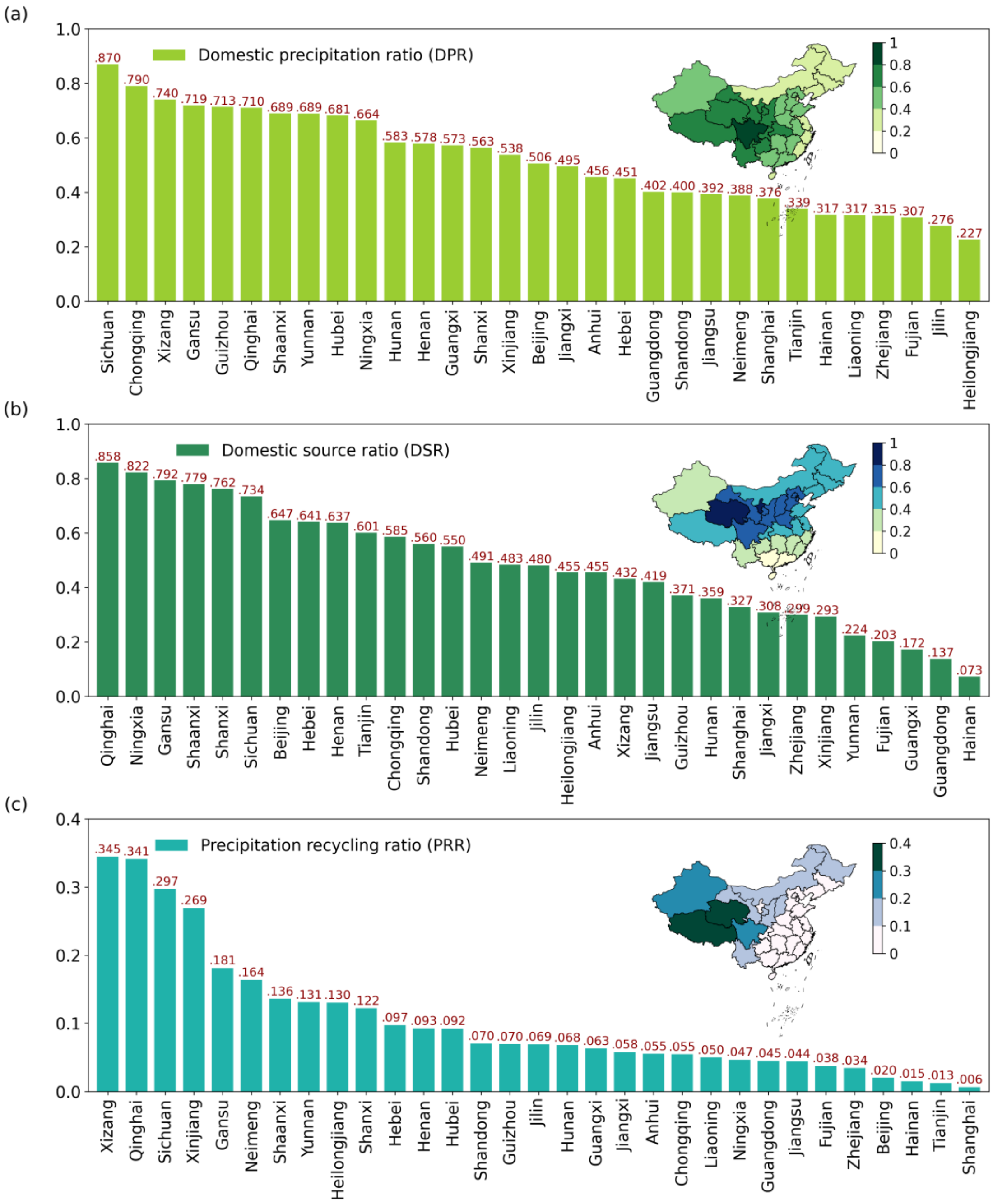

Figure A2. (a) Domestic precipitation ratio (DPR), (b) domestic source ratio (DSR) and (c) precipitation recycling ratio (PRR) in each province.

Line 214: Provide a definition of westerly winds for a general audience. Also, it is the first time in the manuscript that atmospheric circulation is considered explicitly (see comment about the Introduction)

Response: Thank you for the comments.

In the revision, we provided the definition of westerly in Section Introduction. The revised texts are shown below:

The general spatial and seasonal patterns of moisture flows in China are determined by regional atmospheric circulation systems, including prevailing westerly winds (from the west toward the east) in most of China between 30° and 60° (Bridges et al., 2023), the East Asian monsoon in eastern China, and India monsoon in southwestern China.

Section 3.2:

Suggest swapping the order with Section 3.1. The geographic visualization of flows in Section 3.2 aids in understanding the results presented in Section 3.1.

Response: Thank you for the comments.

Section 3.1 shows the network of interprovincial green water flows. Section 3.2 shows the spatial pattern of each province's composited green water flows direction based on the green water flowing network. We think it's more appropriate to clarify the interprovincial green water flowing network firstly.

In the revision, we streamlined 3.1 and 3.2, and merged them. The revised texts are shown below.

3.1 The interprovincial green water flows in China and their directions

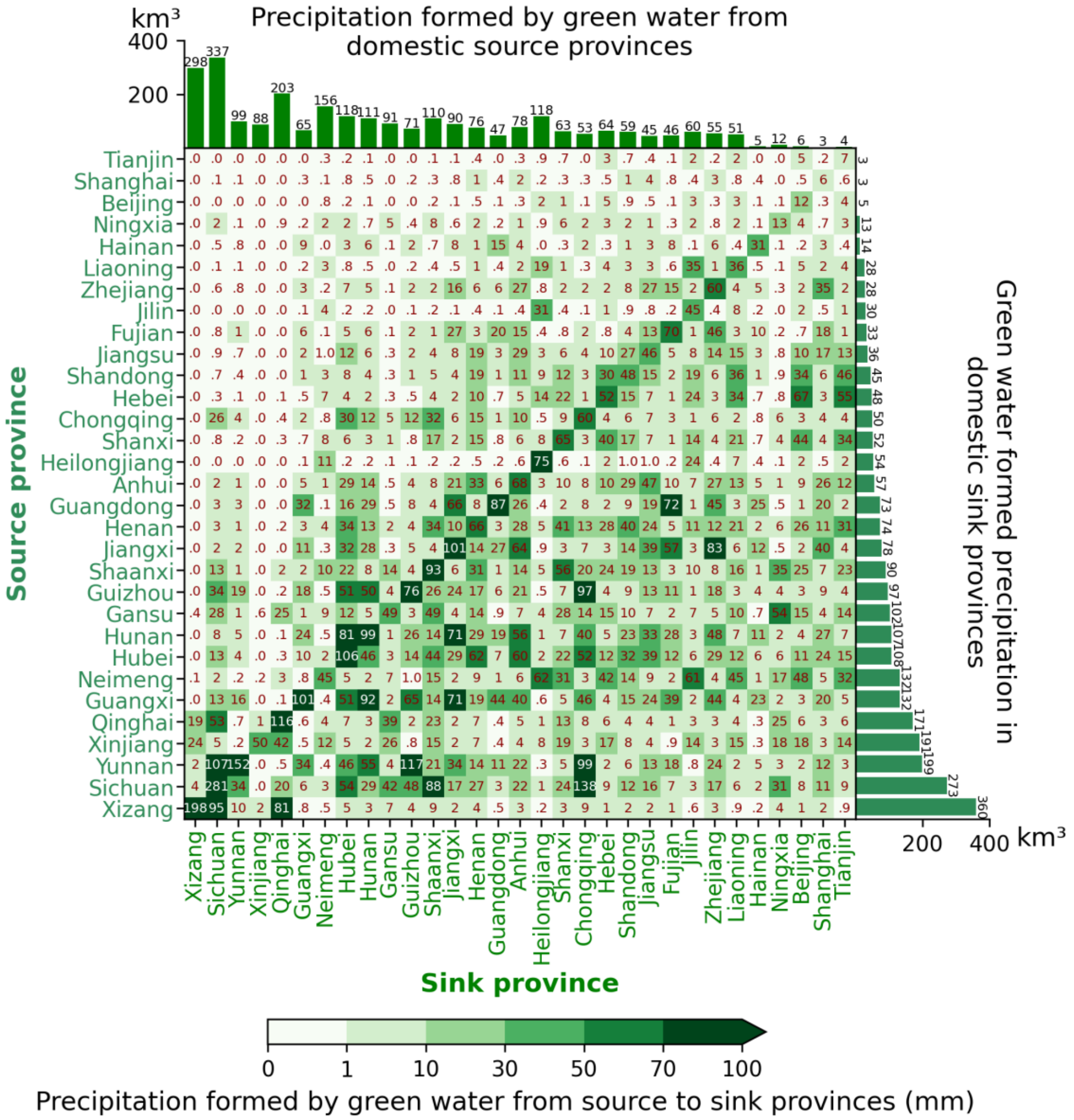

Figure 2. Interprovincial green water flows in China. The heat map denotes precipitation in sink province generated by green water from a source province (mm). The right bar shows domestic precipitation (km^3) formed by green water from each source province. The top bar shows precipitation in each sink province formed by green water from domestic source provinces (km^3).

Green water exported from a source province forms precipitation in different sink provinces in China, and precipitation in a sink province originates from green water in different source provinces. Therefore, different provinces in China, acting either as sources or sinks, are interconnected through moisture recycling and established an interprovincial network (Fig. 2).

A large fraction of green water exported from each source province is retained locally to generate precipitation (diagonal cells in Fig. 2). The precipitation recycling ratio (PRR), the ratio of precipitation generated by local green water to total precipitation, reflects how much green water of each source province contributes to its own precipitation (Fig. A2c). Xizang has the highest PRR of 0.345, followed by Qinghai (0.341) and Sichuan (0.297). Besides local recycling, green water predominantly flows and generates more precipitation in neighboring provinces and less in distant provinces. For example, green water from Sichuan forms high precipitation in neighboring provinces such as Chongqing (138 mm), far surpassing other distant sink provinces (< 88 mm).

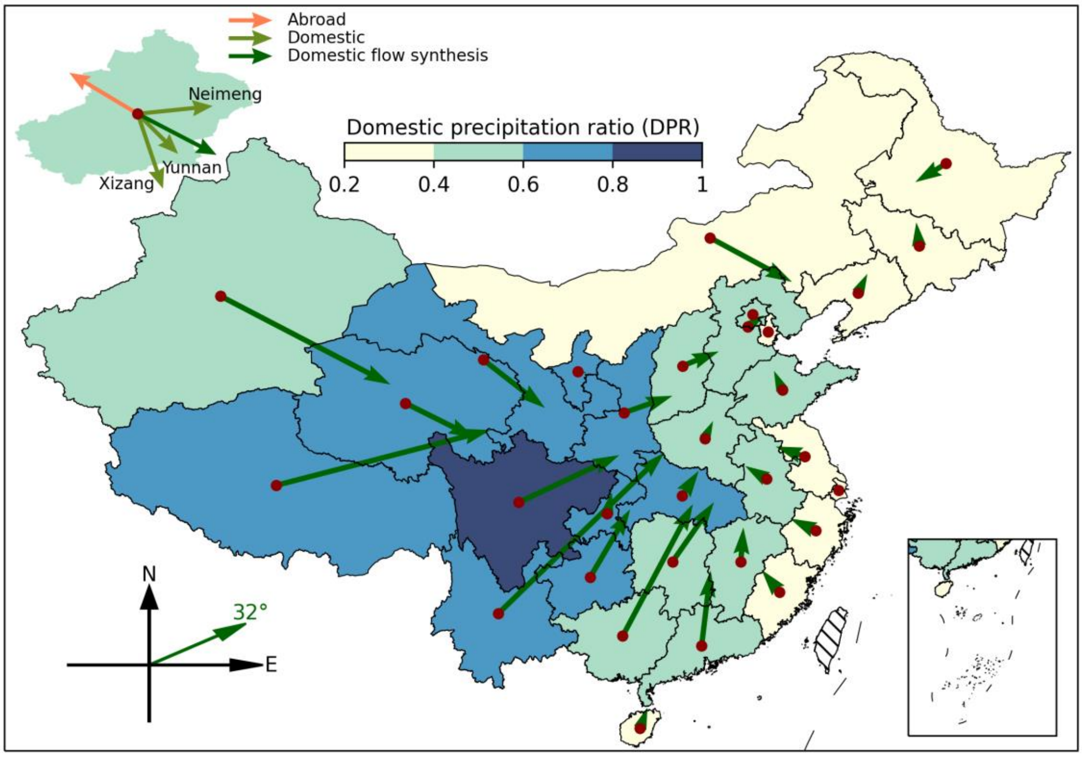

Figure 3. Direction of green water flows from each source province in China. Green arrows indicate the average direction of domestic green water flows, denoted as a vector starting from a source (the geometric center in red points) to sink provinces and with its length representing the amount of precipitation formed by green water. The face colors on the map represent fractions of green water formed precipitation within China of each source province (DPR). The upper left corner is a schematic diagram for green water flows from Xinjiang. The lower left corner is the composite flow direction of interprovincial green water of all provinces.

The direction of interprovincial green water flow can be visualized as a composite direction averaging all domestic green water flows from each source province, which are mainly determined by atmospheric wind conditions, source location, and green water volume (Fig. 3). Overall, the average direction of all interprovincial green water flows is at 32° northeastward (32° north off the east direction), suggesting green water within China is transported to the north and east directions owning to combined effects of monsoons and westerly.

Green water exported by source provinces contributes to precipitation both within and outside China. We defined the domestic precipitation ratio (DPR) as the ratio of green water that formed precipitation in China to each province's total green water export to represent their relative importance to China's precipitation (Fig. A2a). Green water from provinces in western and central China mainly flows eastward under the influence of prevailing westerlies, which extend their evaporationsheds eastward to cover a large territory of China and generate more precipitation within China (Fig. 3). For instance, green water from Xizang, the largest exporter in China, produces the largest domestic precipitation (360 km^3) (right bar on Fig 2) with a high DPR of 0.74, contributing to precipitation in other 30 provinces with varying extents (0.2 to 95 mm). Similarly, the green water from southern provinces is affected by the Indian Ocean Monsoon (southwest monsoon), which drives green water flowing northeastward. With a substantial volume of green water, these southern provinces contribute significantly to domestic precipitation. In contrast, green water from eastern coastal or northwest border provinces goes to the northwest primarily attributed to the East Asian Monsoon (southeast monsoon) (Cai et al., 2010). As a result, most evaporationsheds laid outside China generate less domestic precipitation but more outside the country, resulting in a lower DPR, such as Fujian (DPR 0.31) and Heilongjiang (DPR 0.23). The northern provinces are influenced by westerly winds and winter monsoon from Siberia (Sun et al., 2012), causing predominantly southeastward flow of green water. However, evaporationsheds of these provinces mainly cover the Pacific Ocean, resulting in a relatively low DPR despite their substantial volume of exported green water. While some inland provinces have a high DPR because their evaporationsheds overlap with mainland China, the low green water volume (Fig. A4) limits their domestic precipitation contribution (e.g., Gansu and Ningxia with DPR of 0.72 and 0.66, respectively).

Furthermore, precipitation in sink provinces originates from both domestic and foreign green water sources. Sichuan (337 km^3), Xizang (298 km^3), and Qinghai (203 km^3) are the top 3 provinces importing the largest volume of green water from domestic sources due to the large ET from themselves and neighboring provinces (top bar of Fig 2). To quantify the relative importance of domestic sources, we defined the domestic source ratio (DSR) in each province as the sum of precipitation contribution from domestic sources divided by total precipitation (Fig. A2 (b)). DSR is related to each province's precipitationshed (i.e., upwind region contributing evaporation to a specific location's precipitation) (Keys et al., 2014) and the included domestic green water exporters. The highest DSR found in Qinghai (0.86) and Ningxia (0.82) is because their precipitationsheds include large domestic green water exporters like Xinjiang and Xizang, which supply considerable green water traveling eastward. Conversely, Hainan (0.07) and Guangdong (0.14) in coastal areas have lower DSR because their precipitationsheds are primarily located in oceans and other countries due to the influence of the summer monsoon (Cai et al., 2010).

Section 3.3:

This section is well-written and interesting. However, given its significance to the analysis, consider expanding and providing more in-depth discussion.

Response: Thank you for the comments.

The in-depth discussion of Section 3.3 is in the Section Discussion. To make this part clearer, we moved the in-depth discussion to Section Results in the revision. The revised texts are shown below.

3.3 Changing socio-economic values of green water flows

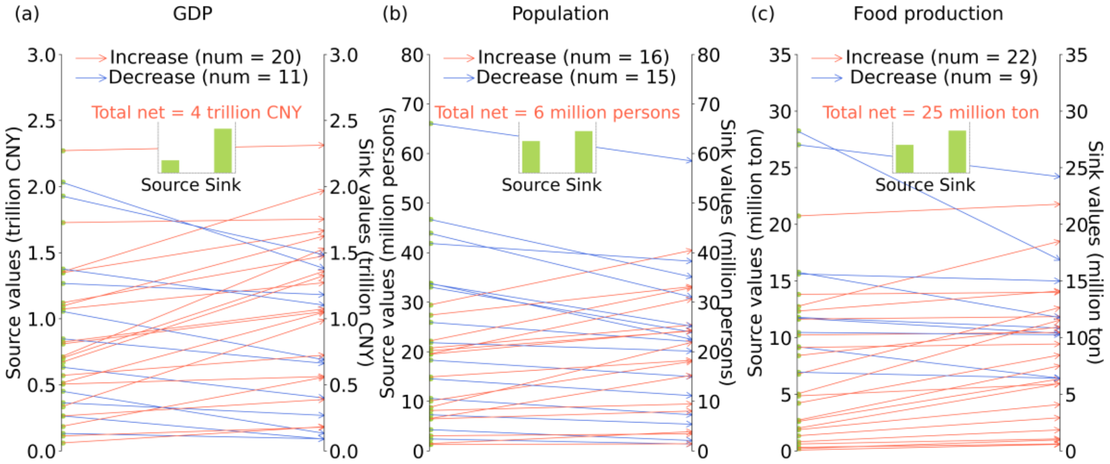

Figure 5. Changes in socio-economic values embodied in green water flow from source to sink provinces for GDP (a), population (b), and food production (c). Thin arrows of different colors represent the socio-economic value increase (in red) or decrease (in blue) from source to sink provinces. Green bars represent the sum socio-economic value in China's 31 provinces.

The substantial socio-economic values embodied in interprovincial green water flows highlight the teleconnection of green water from source provinces and the socio-economy in sink provinces, including economy, population, and food production. Due to different socio-economic statuses, the same amount of consumed water resources, which are recharged by green water, would sustain different socio-economic values between source and sink provinces. Therefore, the socio-economic values embodied in green water flow would change when traveling from source to sink provinces. As shown in Fig. 5, the socio-economic values embodied in green water flow increase from source to sink provinces by 4 trillion CNY for GDP, 6 million for population, and 25 million tons for food production, respectively. The increase in the embodied GDP, population, and food production is observed in 20, 16, and 22 source provinces among a total of 31. This indicates that green water tends to flow from less to more developed provinces, sustaining more economic production, population, and food production per unit of green water. The largest economic output value increases are in Guangxi (+0.83 trillion CNY, 54%). Xinjiang has the most added value in population (+13 million persons, 59%) and food production (+7 million tons, 60%) because their green water flows to more developed provinces (Fig. A5). In contrast, decreased socio-economic values of green water flow are also observed. Shandong, Shaanxi, and Henan have the largest depreciation in green water values for GDP (-0.66 trillion CNY, 48%), population (-13 million persons, 42%), and food production (-12 million tons, 72%) (Fig. A5) because their green water flows to provinces with lower socio-economic values.

The changing socio-economic values of green water flow reflect the regional disparity in socio-economic statuses between source and sink provinces. The exported green water for more than half of the source provinces in China (> 15) has increased socio-economic values when reaching sink provinces. This shows that green water from less developed provinces effectively supports the higher socio-economic status of developed provinces through the interprovincial flow network. Therefore, these provinces are vitally important green water providers to developed areas. This teleconnection of green water and socio-economy substantiates that changing land use in the source provinces that affect evapotranspiration is likely to influence water resources availability and socio-economic development in the sink provinces (Dias et al., 2015; Weng et al., 2018). Hence, it is imperative to account for “invisible” green water flow and its cascade effect in large-scale water resources management.

Discussion:

Overall, this section is well-structured and written, but improvements are needed: Enlarge Figure 5 for greater clarity.

Response: Thank you for the comments.

In the revision, we enlarged Figure 5, and the revised figure is shown below:

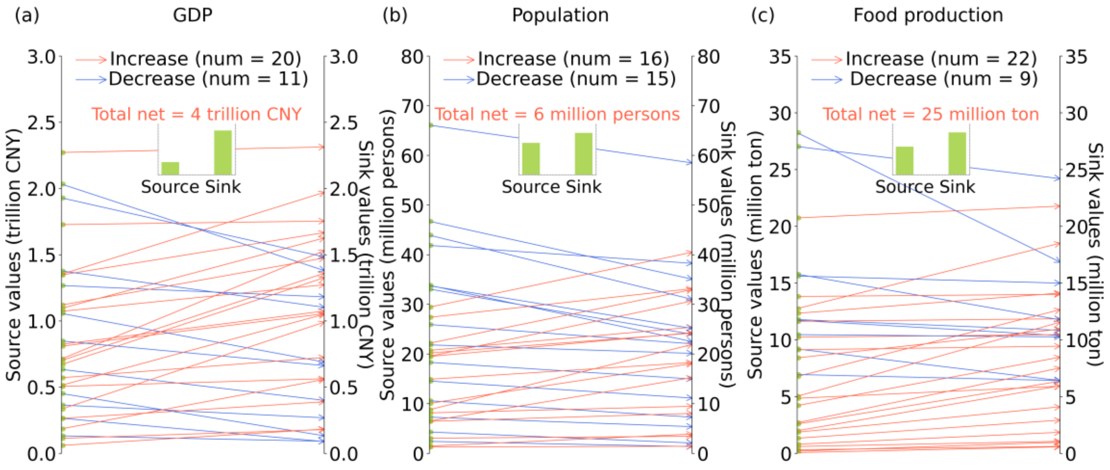

Figure 5. Changes in socio-economic values embodied in green water flow from source to sink provinces for GDP (a), population (b), and food production (c). Thin arrows of different colors represent the socio-economic value increase (in red) or decrease (in blue) from source to sink provinces. Green bars represent the sum socio-economic value in China's 31 provinces.

Provide a deeper discussion on the uncertainty of tracked precipitation at the provincial level.

Response: The uncertainty of tracked precipitation includes three aspects: (1) different ET and precipitation datasets lead to different precipitation contribution and PRR due to the ET amount and spatial distribution; (2) the non-closure of the moisture balance between ET and precipitation from ERA5 results in inaccurately capturing actual ET and precipitation volumes; (3) the moisture tracking model has some assumption and simplification. The purpose of our work is not to precisely quantify the moisture recycling quantification but to reveal the relationship between the moisture and socio-economy.

The revised texts in section Discussion are shown below:

Due to the complex dynamics of the green water flow and limitations of the moisture tracking model, there are still major uncertainties in data and methods of this study. First, ET and precipitation datasets driving the UTrack model affect the tracked trajectories and magnitude of moisture flow. The resulting moisture trajectory is expressed as the fraction of ET to precipitation, and the exact amount of moisture is restored by the ET and precipitation datasets chosen by users. Different ET and precipitation datasets could lead to different precipitation contributions and PRR (Li et al., 2023). We used the ERA5 dataset to keep consistent with the original UTrack model. It is noted that the non-closure of the moisture balance from ERA5 (De Petrillo et al., 2024) and simplifications and assumptions introduced in the moisture tracking model also add uncertainty in the moisture tracking (Tuinenburg and Staal, 2020).

Lines 429-431: The sentence "Our attempt... [..]" is redundant here and would be more appropriate at the end of the discussion.

Response: Thank you for the comments.

In the revision, we moved this sentence to the end of the discussion.

Nevertheless, our assessment serves as a useful first step to demonstrate the importance of the tele-connected green water flow in addition to blue water. Our attempts to quantify the socio-economy embodied in green water flow fill the gap in green water value assessment and provide a methodological reference for green water management.

General Comments for Discussion and Conclusions:

Include a more in-depth description of the limitations of the socio-economic analysis to add value to these sections and the overall study.

Response: Thank you for the comments.

The limitation of the socio-economic analysis includes:

(1) The green water's socio-economic contribution excludes green water flowing abroad, and did not separate water sources in assessing socio-economic contribution and consider the accessibility of precipitation formed by green water to human activities.

(2) The research selected three socio-economic indices which are tightly linked to the water resources. Other indices linked to water resources like livestock production and irrigated agriculture are not considered.

In the revision, we added these limitations in the section Discussion, and the revised texts are shown below:

Secondly, the socio-economic value assessment of green water in this study only considers green water flows within China, excluding flows moving abroad and to the ocean that may embody socio-economic value beyond the territory of mainland China. We mainly attribute socio-economic values to green water and generated precipitation because precipitation is the ultimate water source for recharging surface and groundwater of a region. Strictly speaking, such attribution needs to be more precise because socio-economy also utilizes streamflow from upstream areas, which deserve separate attention.

In addition, not all water resources replenished by green water-induced precipitation are accessible for human activities since part of them is used by the natural ecosystem (Keys et al., 2019). Therefore, it is necessary to distinguish water sources and consumption to account green water values more accurately. Despite the selected socio-economic indicators closely linked to water resources, green water flows' socio-economic contribution can manifest in other aspects such as livestock production and irrigated agriculture. In future studies, the dynamic linkage between green water, water resources and economic development can be assessed annually by using a long-term moisture tracking dataset with a separation of water sources consumed by socio-economy (surface and groundwater).

Discuss potential improvements for this type of socio-economic analysis.

Response: Thank you for the comments.

Potential improvements for this type of socio-economic analysis include (1) the moisture recycling dataset improving; (2) the interannual variations analysis of green water's socio-economic contribution; (3) the distinguish of blue and green water source; (4) more comprehensive assessment of the green water's contribution.

In the revision, we added these potential improvements in the section Discussion, and the revised texts are shown below:

Due to the complex dynamics of the green water flow and limitations of the moisture tracking model, there are still major uncertainties in data and methods of this study. First, ET and precipitation datasets driving the UTrack model affect the tracked trajectories and magnitude of moisture flow. The resulting moisture trajectory is expressed as the fraction of ET to precipitation, and the exact amount of moisture is restored by the ET and precipitation datasets chosen by users. Different ET and precipitation datasets could lead to different precipitation contributions and PRR (Li et al., 2023). We used the ERA5 dataset to keep consistent with the original UTrack model. It is noted that the non-closure of the moisture balance from ERA5 (De Petrillo et al., 2024) and simplifications and assumptions introduced in the moisture tracking model also add uncertainty in the moisture tracking (Tuinenburg and Staal, 2020). Moreover, the resulting moisture trajectory data only represent the climatologically average moisture trajectories and ET (Li et al., 2023), neglecting the interannual variability in moisture flow trajectory, e.g., those induced by the influence of extreme weather events or ENSO (Zhao and Zhou, 2021). The interannual variations in green water flow may affect DPR and DSR in some provinces. Human adaptation tends to buffer the impacts of interannual variations on the socio-economy through water resource management such as reservoirs, dams, and other infrastructure. Accounting for interannual variations in green water flows and their socio-economic contribution is worth further investigation. Secondly, the socio-economic value assessment of green water in this study only considers green water flows within China, excluding flows moving abroad and to the ocean that may embody socio-economic value beyond the territory of mainland China. We mainly attribute socio-economic values to green water and generated precipitation because precipitation is the ultimate water source for recharging surface and groundwater of a region. Strictly speaking, such attribution needs to be more precise because socio-economy also utilizes streamflow from upstream areas, which deserve separate attention.

Moreover, the interactions between blue and green water increase the complexity to evaluating green water's socio-economic contribution. For example, the blue water extracted by irrigation increases ET in the source region, providing more moisture for downwind regions (Yang et al., 2019). Simultaneously, most of the blue water for local irrigation comes from the green water of upwind regions (McDermid et al., 2023). In addition, not all water resources replenished by green water-induced precipitation are accessible for human activities since part of them is used by the natural ecosystem (Keys et al., 2019). Therefore, it is necessary to distinguish water sources and consumption to account green water values more accurately. Despite the selected socio-economic indicators closely linked to water resources, green water flows' socio-economic contribution can manifest in other aspects such as livestock production and irrigated agriculture. In future studies, the dynamic linkage between green water, water resources and economic development can be assessed annually by using a long-term moisture tracking dataset with a separation of water sources consumed by socio-economy (surface and groundwater).

Since this study is presented as a starting example of integrating green water teleconnections into water management strategies for socio-economic applications, it would be beneficial to elaborate on additional steps needed to achieve this goal.

Response: Thank you for the comments.

In the revision, we added these potential improvements in the section Discussion, and the revised texts are shown below:

In future studies, the dynamic linkage between green water, water resources and economic development can be assessed annually by using a long-term moisture tracking dataset with a separation of water sources consumed by socio-economy (surface and groundwater). Nevertheless, our assessment serves as a useful first step to demonstrate the importance of the tele-connected green water flow in addition to blue water. Our attempts to quantify the socio-economy embodied in green water flow fill the gap in green water value assessment and provide a methodological reference for green water management.

Consider discussing other variables that could enhance the analysis of socio-economic implications.

Response: Thank you for the comments.

Some other socio-economic variables like livestock and irrigated agriculture may enhance the analysis. In the revision, we added them and the revised texts are shown below:

Despite the selected socio-economic indicators closely linked to water resources, green water flows' socio-economic contribution can manifest in other aspects such as livestock production and irrigated agriculture.

Supplementary Figures and Tables are not cited, and thus integrated in the text. Please integrate them in the main text.

Response: Thank you for the comments.

We apologize for the confusion regarding the figures citing and Supplementary Figures and Tables citing. In the main text, supplementary figures were cited as Fig. A1, Fig. A2; supplementary tables were cited as Table A1 and Table A2. All supplementary figures and tables were cited in section Result and Discussion.

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