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Revealing Trade Potential for Reversing Regional Freshwater Boundary Exceedance

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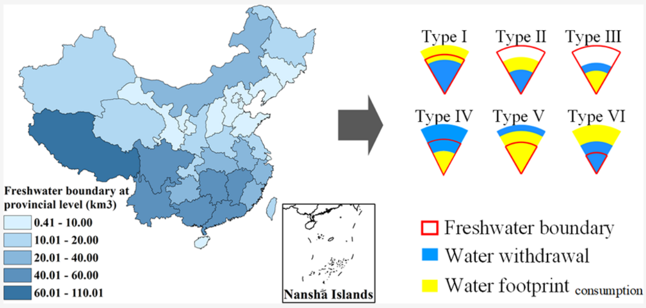
ABSTRACT: Applying the planetary boundary for the freshwater framework at the regional level is important in supporting local water management but is subject to substantial uncertainty. Previous estimates have not fully investigated the potential of trade in mitigating regional freshwater boundary (RFB) exceedance. Here, we estimate RFB based on the average results of 15 different hydrological models to reduce uncertainty. We then propose a framework to divide the RFB exceedance/maintenance into contributions from both consumption and trade and further identify trade contribution into six types. We applied the framework to China's provinces, which are characterized by intensive interprovincial trade and a significant mismatch in water resource supply and demand. We found that the current trade pattern limits the role of trade to mitigate RFB exceedance. For the importing provinces exceeding RFBs, 78% of their imported goods and services came from other RFB exceeding provinces. Scenario analysis showed that relying on increased imports alone, even to its greatest extent, will not reverse RFB exceedance in most importing provinces. Increased imports, however, will have an aggregate effect on the trade partners, leading to the exceedance of the national freshwater boundary. We also found that promoting export of goods and services from non-RFB exceeding provinces and reducing their water intensity will help address the imbalance both locally and, in the aggregate, nationally.



KEYWORDS: *planetary boundary, gap to water sustainability, trade, water footprint*

■ INTRODUCTION

Freshwater is a vital but limited resource for both humans and ecosystems. Understanding the gap between human water demand and the carrying capacity of water resources is an important step toward achieving strong sustainability of water resources.[1,2] The planetary boundary for freshwater, which sets limits for freshwater use, has attracted broad attention in addressing this goal.[3−5] This indicator provides a maximum amount of blue water consumption (control variable at the global level), beyond which profound consequences to the Earth system might occur.[3,6] When a planetary boundary for freshwater is applied at different local levels, such as the grid level, river basin level, and national level, the localized freshwater boundary has been exceeded in many regions of the world (using blue water withdrawal as the control variable).[6−8] Such regional exceedances will generate further global impacts, illustrating the necessity of defining the freshwater boundary at finer scales.[6] For example, regional increases in water withdrawal have increased global evapotranspiration.[9] Addressing the freshwater boundary at the local level will support water management strategies in the local context considering regional differences in water endowment and social and economic water demands.[6,7,10]

Trade plays an important role in linking freshwater boundary assessment from local to global scales.[4,5,11,12] Imports of goods and services may replace local economic activity and, thus, reduce water withdrawal,[13] hence preventing possible regional freshwater boundary (RFB) exceedance. In contrast, the expansion of export activities will likely increase the risk of RFB exceedance. From an interregional perspective, a region operating within its RFB through importing more virtual water, i.e., freshwater used in the production or provision of goods and services, may jeopardize the water resources of a water-scarce exporting region. This, in turn, may result in exceedance of RFB of the exporters, which in the aggregate may increase the risk of planetary freshwater boundary exceedance.

Studies have assessed the impact of trade on regional water scarcity through relative indicators, such as the water stress index (dividing local water withdrawal by water availabil-

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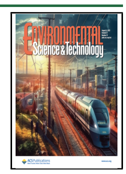

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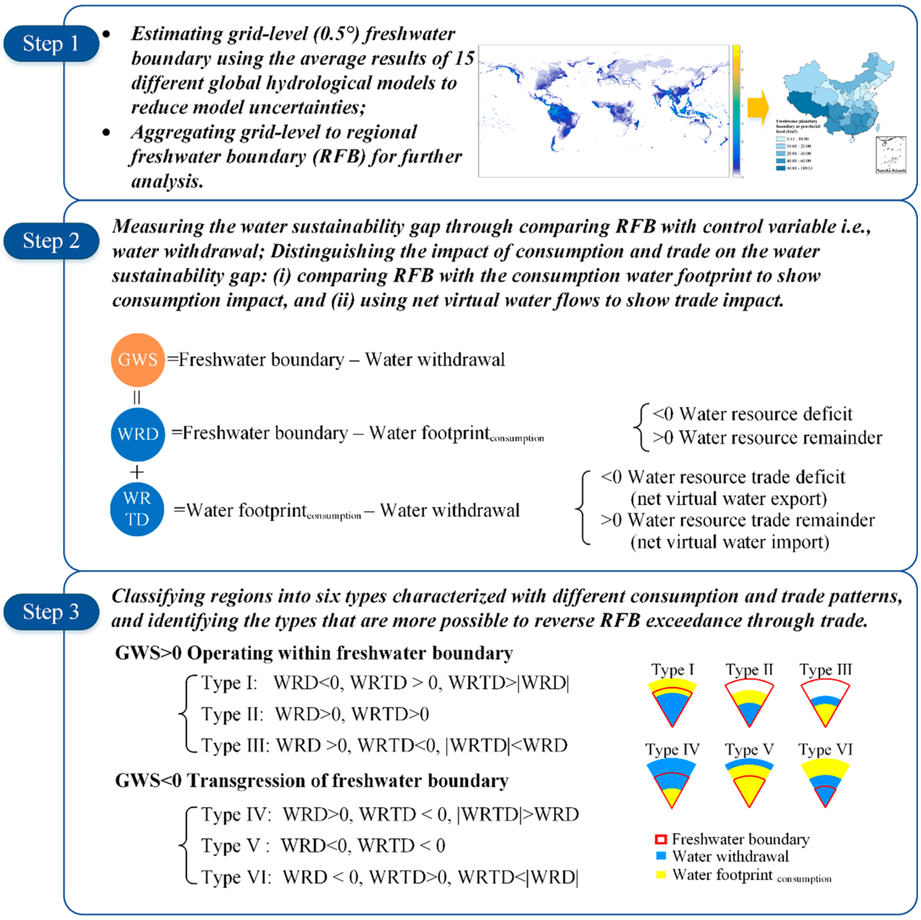

Figure 1. Proposed framework to assess the gap to water sustainability at the local level. The GWS is a measure of the gap between water withdrawal and RFB; the WRD is the result of the comparison between the consumption water footprint and the RFB; and the WRTD is a measure of the net virtual water flow.

ity),[14,15] or water scarcity footprint (water footprint weighted by the water stress index).[16,17] In contrast, the RFB provides an absolute indicator as a complement, which clearly shows the gap to water sustainability through setting a "safe operating space" and aggregate consequences of local exceedance to global exceedance. However, research on the impact of trade on mitigating RFB exceedance is relatively scarce. Existing studies have allocated RFB exceedance to regional consumption (including imports) by comparing the consumption water footprint to RFB.[18] The consumption water footprint of a region can be defined as the total volume of blue freshwater withdrawn along the entire supply chain that is used to produce the goods and services consumed in that region. One approach to calculate the RFB is to use a per capita equal share approach to downscale the planetary freshwater boundary.[19] Another approach is using a bottom-up approach considering differences in local water endowment.[1] Using the bottom-up approach, Li et al.[20] investigated how imports in consumption regions may contribute to RFB exceedance in production regions. In addition, current RFB exceedance analysis is subject to substantial uncertainty and lack of data.[18]

These previous studies have enriched the methodology of the RFB assessment, including trade impacts. However, an important and unanswered question is the extent to which imports may substitute local production activity, thus enabling local water withdrawal to remain within the RFB. This question is closely related to one of the top 100 global water questions, i.e., to what extent can imports be utilized to conserve local water resources.[21] In addition, previous RFB assessment frameworks appear unable to elucidate the role of export to local water overuse, because export is not included in the consumption water footprint accounting framework. A consumption water footprint maintained within the RFB does not necessarily mean that the water resources of a region are managed within a safe operating space. The RFB may still be exceeded as a result of the production expansion of goods and services for export. Overall, water managers are more inclined to understand the role of both imports and exports in RFB exceedance from the local point of view. However, to the best of our knowledge, no existing RFB assessment framework can help water managers achieve this goal.

Here, we propose a framework to assess the impacts of trade flows on the gap to local water sustainability, i.e., RFB exceedance (Figure 1). Our framework may also identify the potential of reversing RFB exceedance through strengthening of selected trade links. The framework is distinguished from previous frameworks by (i) estimating grid-level (0.5°) RFB using the average results of 15 different global hydrological models to reduce model uncertainty, (ii) considering the impact of both import and export of traded goods and services on RFB exceedance, (iii) identifying six different types of contributions that trade makes to RFB exceedance/maintenance to evaluate regional characteristics, which may then enable maintenance within RFB through trade, and (iv) having

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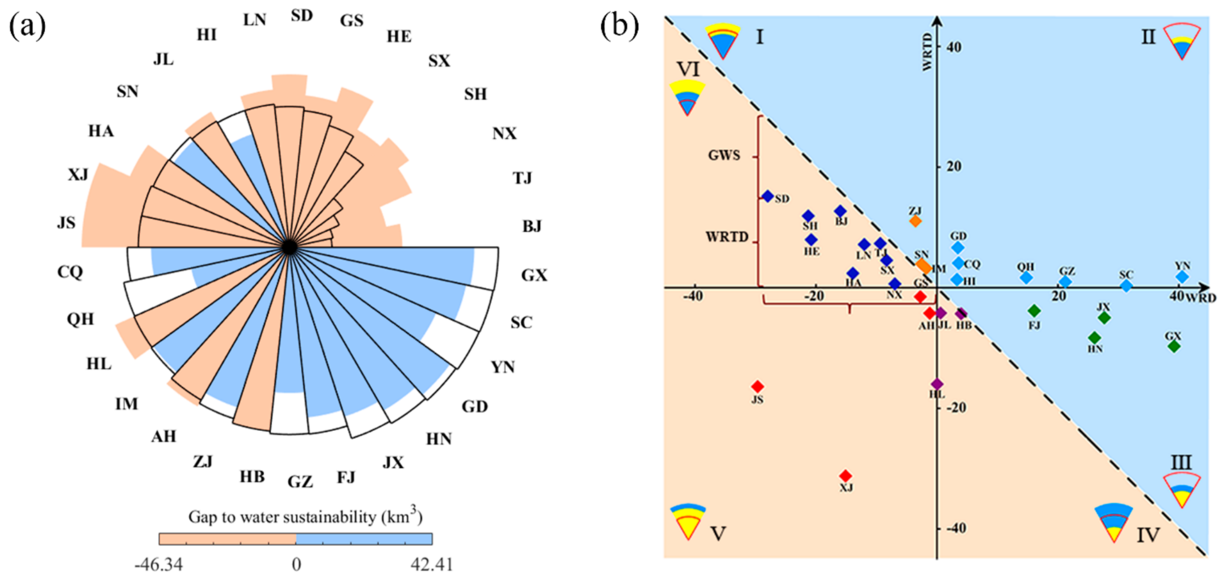

Figure 2. (a) Gap to water sustainability in China's provinces and (b) distribution of China's provinces, distinguishing the contributions of consumption and trade to RFB exceedance into six quadrants. In panel a, the black segments denote the provincial RFB, and the colored bars represent the volume of provincial water withdrawal. Provinces whose water withdrawal exceeded their RFBs are marked in orange, whereas provinces remaining within their RFBs are colored blue. In panel b, the WRD indicator is set as the *x* axis and WRTD is set as the *y* axis. The dashed line is where the GWS equals zero. The blue zone above the dashed line indicates a state in which the value of GWS is positive; i.e., the provinces in this zone are operating within RFB, covering quadrants I, II, and III. The orange zone below the dashed line represents where GWS is negative, which means that the provinces in this zone are exceeding their RFBs, i.e., covering quadrants IV, V, and VI. For simplicity, abbreviations are used to represent different provinces, and the corresponding name is shown in Table S2 of the Supporting Information.

the ability to evaluate the potential of trade contribution in reducing the gap to water sustainability. Here, the gap to water sustainability (GWS) is defined as the gap between water withdrawal and RFB. The framework was developed by combining a bottom-up RFB assessment approach with multiple global hydrological models, multi-region input–output analysis (MRIO), and the categories of "ecologically unsustainable trade".[22] We applied our framework to evaluate the potential of interregional trade to reverse RFB exceedance at the provincial level in China. A national-level assessment of large countries, such as China or the U.S., will mask regional differences in water demand and water endowment. A provincial-level analysis can better address the spatial heterogeneity of water resources and trade impacts in large countries.[15,23] Chinese provinces are the major geopolitical units in China, and many water resource policies, such as "cap to water withdrawal", are implemented at this level.[24,25]

Analytical Framework. Our framework started by estimating the RFB using a bottom-up approach, which accounts for the spatial heterogeneity of water resources (step 1). The RFB was first achieved at the grid level (0.5°) and then aggregated to the provincial level for, in our case, further analysis. The next step (step 2) was to investigate the GWS at the local level, which compares the RFB to regional water withdrawals. The negative value of GWS means the region has exceeded the safe operating space for blue freshwater withdrawal, while the positive value shows that the region still operates within its RFB. In step 2, we further attributed the exceedance of RFB to two causes (Figure 1), namely, (1) overconsumption, i.e., the consumption water footprint exceeding RFB [resulting in a water resource deficit (WRD) < 0], and (2) net export of virtual water to other provinces [resulting in a water resource trade deficit (WRTD) < 0]. Our framework thus includes the impact of both import and export of traded goods on RFB exceedance. Virtual water flows account for water withdrawal, which is embodied into goods and services in the exporting provinces to importing provinces. Note, we did not include water embodied in international imports in the provincial consumption water footprint and virtual water flow accounting. In other words, we only consider the impact of provincial consumption and trade on water withdrawal within China (see Figure S1 of the Supporting Information for the system boundaries of our research). The motivation for our framework originated from the comparison between the ecological footprint and biocapacity.[26] This ecological footprint analysis framework is regarded as the greatest step forward when evaluating strong sustainability in absolute terms.[26,27] Further, in step 3, our framework was inspired by the categories of "ecologically unsustainable trade", which classifies regions in accordance with their ecological deficit and trade status.[22] This enabled our six-category classification of the contributions of both consumption and net virtual water export to the water sustainability gap (Figures 1 and 2b). This six-quadrant approach was designed to show the complex interactions that trade has on the water sustainability gap.

MATERIALS AND METHODS

Estimating the Regional Freshwater Boundary. A bottom-up RFB estimation approach allocates different percentages of river runoff to environmental flow requirements (EFRs) according to different flow seasons. The estimation starts at the grid level (0.5°), which shows the hydrographic variability from different regions and may be aggregated to obtain RFB at various spatial scales (river basin, provincial, national, etc.). A variety of methods have been proposed to estimate EFRs.[28] We adopted a rigorous allocation for EFRs, i.e., 40% of the mean monthly flow during the high-flow season (when the mean monthly flow is larger than the mean annual flow), 40% of the mean annual flow during the intermediate-flow season (when the mean monthly flow is 40−100% of the mean annual flow), and 100% of the mean monthly flow during the low-flow season (when the mean monthly flow is ≤40% of the mean annual flow).[29] We utilized this method because of its demonstrated rigor, which is crucial for balancing water resources and human development and providing a greater degree of protection for ecological flows[30−32] (SI Note 1 of the Supporting Information). An uncertainty of ±15% was exhibited when adopting different EFR methods.[6] The RFBs were placed at the lower end of the uncertainty range

$$\mathrm{RFB} = \sum_{i=1,\ldots,12} (\mathrm{MMF} - \mathrm{EFR} - 0.15\mathrm{MMF}) \tag{1}$$

where MMF is the mean monthly flow (km^3/m), EFR is the environmental flow requirement (km^3/m), and the term 0.15MMF represents the uncertainty range for EFR estimates (SI Note 2 of the Supporting Information). Monthly estimates were then summed to the annual RFB ($km^3/year$).

As the basis for RFB quantification, mean monthly flows were computed with 15 global hydrological models, including LPJmL, H08, WAYS, WEB-DHM-S, CLM40, DBH, JULES-B1, JULES-W1, MATSIRO, MPI-HM, ORCHIDEE, PCR-GLOBWB, SWBM, VIC, and WaterGAP2.2.[33] We selected these 15 models because they all follow the ISIMIP2a platform protocol, which provides high-resolution information on runoff features and facilitates model intercomparison on both regional and global scales[34] (SI Note 1 of the Supporting Information). The main differences of these selected models in the land-surface hydrological simulation process can be found in Table S1 of the Supporting Information. Driven by ISIMIP2a simulation protocols, these models used the daily observed climate data on a global 0.5° grid cell from the Global Soil Wetness Project Phase 3 (GSWP3) as input.[35] These hydrological models were set in the mode of naturalized, which simulates river flows without human impacts.[33] The runoff was simulated at a spatial resolution of 0.5° on a daily time step between 1971 and 2010, before being aggregated into monthly flows and averaged over 40 years. We compared the simulated runoff with measured values for six global basins, and the Nash−Sutcliffe efficiency (NSE) was greater than 0.7,[33] indicating that the simulation results were good.[36] We further took the ensemble mean runoff of the 15 models to eliminate the model error. Uncertainty analysis showed that using the ensemble mean runoff reduced uncertainty compared to using a single model (see SI Note 2 of the Supporting Information).

Measuring the Gap to Water Sustainability. The GWS indicator was proposed as a measure of the gap between water withdrawal and RFB.

$$\mathrm{GWS} = \text{regional freshwater boundary} - \text{water withdrawal} \tag{2}$$

where GWS < 0 means that the water withdrawal of a region exceeds its RFB, while GWS > 0 means that the region is operating within its RFB. The gap to water sustainability can be further attributed to two causes: (1) overconsumption, i.e., the consumption water footprint exceeds the RFB, and (2) trade-induced net export of virtual water to other regions. Two indicators, i.e., WRD and WRTD, were thus proposed.

The WRD indicator reflects the results of comparison between the consumption water footprint and the RFB

$$\mathrm{WRD} = \text{regional freshwater boundary} - \text{water footprint}_{\text{consumption}} \tag{3}$$

When the WRD is negative, i.e., in a water resource deficit status, the local water endowment cannot meet the final consumption demand of the region. In contrast, a positive WRD is termed the water resource remainder.

The WRTD indicator measures net virtual water flows

$$\mathrm{WRTD} = \text{virtual water import} - \text{virtual water export} = \text{water footprint}_{\text{consumption}} - \text{water withdrawal} \tag{4}$$

When WRTD is negative, i.e., in a water resource trade deficit status, the study region is a net virtual water exporter, and when WRTD is positive, i.e., in a water resource trade remainder status, the region is a net virtual water importer. According to eqs 2−4, GWS may also be expressed as

$$\mathrm{GWS} = \mathrm{WRD} + \mathrm{WRTD} \tag{5}$$

The consumption water footprint was calculated using the MRIO table and the "Water Embodied in Trade" method.[15] It accounts for the impact of the final consumption demand in one region on water resources both within and beyond the region and is summed by the internal water footprint, virtual water import, and domestic water use

$$\mathrm{WFC_r} = \hat{d}_r (I - A_{rr})^{-1} y_{rr} + \sum_{s} \hat{d} (I - A_{ss})^{-1} \left(\sum_{s \neq r} e_{sr} \right) + \mathrm{DWU_r} \tag{6}$$

where $\hat{d}_r(I - A_{rr})^{-1}y_{rr}$ is the internal water footprint, representing the use of regional water resources to produce goods and services consumed by themselves, $\hat{d}_r = w_r/x_r$ is the direct water intensity in diagonal matrix form representing direct water use of each sector per unit of output, $\sum \hat{d}_s(I - A_{ss})^{-1}(\sum_{s\neq r} e_{sr})$ is the virtual water import, also known as the external water footprint, denoting the use of external water resources through imports to meet local demands, $(I - A_{rr})^{-1}$ is the Leontief inverse matrix, where I is the identity matrix, A_{rr} is the technical coefficient matrix, $\hat{y}_{rr}$ is the diagonal matrix for final demand of region r, $\sum_{s\neq r} e_{sr}$ is the import of region r from other regions, and $\mathrm{DWU_r}$ is the domestic water use of region r.

We applied the Chinese MRIO model for the year 2015 to calculate the consumption water footprint and virtual water flows for provinces in China.[37] It comprises 30 economic sectors within 30 Chinese provinces. Taiwan, Hong Kong, Macao, and Tibet were not compiled in the model as a result of a lack of data. Provincial-level water withdrawal data were obtained from the China Water Resources Bulletin[38] and Zhang et al.[39] As far as we know, the most up-to-date provincial-level water withdrawal data with sectoral detail in China are from 2015. Such data were compiled according to Zhang et al.,[39] which provided water withdrawal data from 58 economic sectors and over 294 cities in China in 2015. Specifically, we aggregated the city-level water withdrawal data to the provincial level and match them to the provincial water withdrawal data in the China Water Resources Bulletin, and we further aggregated the sectoral water withdrawal data fitting the sectoral details of the 2015 Chinese MRIO table. In contrast,

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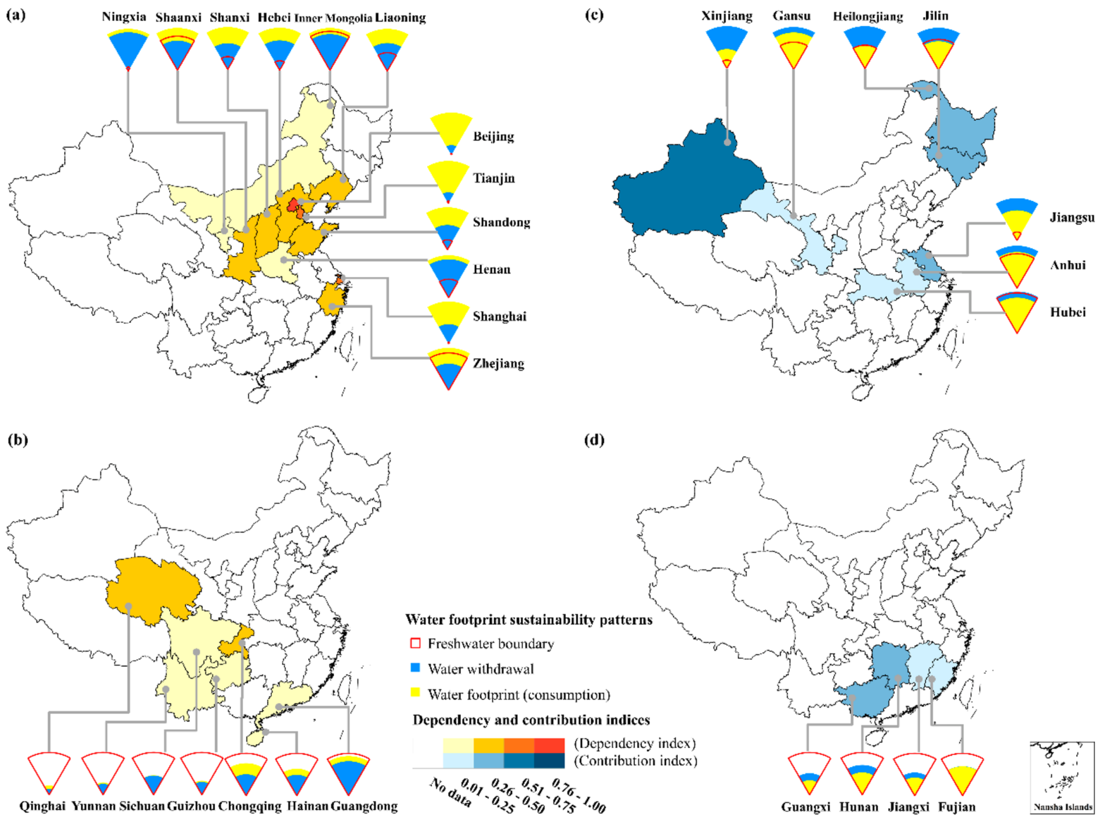

Figure 3. Exploring the relationship between trade patterns and the water sustainability gap: (a) net virtual water importing provinces in water resource deficit, (b) net virtual water importing provinces with a water resource remainder, (c) net virtual water exporting provinces exceeding their RFBs, and (d) net virtual water exporting provinces within their RFBs. The color of each province in the maps represents the value of its dependency (orange) or contribution (blue) index. The fan shapes represent six types of consumption and trade.

existing studies used sectoral water withdrawal data from year 2008[40] and extrapolated the data to match industrial water withdrawal data with sectoral details in specific years, for example, 2007, 2012, and 2017.[41,42] However, extrapolated results based on 2008 data may be biased as a result of structural changes in the Chinese economy.[43] It should be noted that our case focused on the impact of interprovincial trade on water resources within China. Hence, the virtual water flows embodied in international imports of each province were ignored but may be referred to in existing studies.[24,44,45]

■ RESULTS

Comparison between Water Withdrawal and Regional Freshwater Boundary at the Provincial Level. China's national water withdrawal (607.2 km^3) in 2015 was within the national freshwater boundary (646.4 km^3). This is consistent with the evaluations based on top-down approaches reported by other studies.[20,46,47] However, when considering the provincial level, over half of China's provinces had exceeded their RFBs (Figure 2a). Generally, provinces in south China were found to have larger per capita and absolute RFBs (Figures S2 and S3 of the Supporting Information). The sum of all provincial-level gaps amounted to −188.6 km^3, indicating a substantial exceedance of the RFB at the provincial level. Hence, quantifying the gap to water sustainability at the sub-national level is important for large countries, such as China or the U.S. The top five provinces contributing to provincial-level exceedance were Xinjiang (−46.3 km^3), Jiangsu (−46.1 km^3), Heilongjiang (−15.9 km^3), Hebei (−12.8 km^3), and Shandong (−12.8 km^3). We also used the ratio of provincial exceedance to water withdrawal, defined as an exceedance rate, to show the relative severity of the exceedance (SI Note 1 of the Supporting Information). Shanghai, Ningxia, and Beijing were the provinces with the highest exceedance rates, although they did not have a large exceedance in absolute terms (SI Note 1 and Figure S4 of the Supporting Information). The dominant contributing sectors in provincial-level exceedance were "agriculture" (−127.4 km^3 or 67% of the total exceedance), followed by "domestic water use" (−17.1 km^3 or 9% of the total exceedance); see Figure S5 of the Supporting Information.

Contributions of Consumption and Trade to the Exceedance of the Regional Freshwater Boundary. As seen in Figure 2b, provinces in quadrants I, II, and III remained within their RFBs. However, trade and final consumption showed distinct effects in keeping these provinces in different quadrants within their RFBs. For the three provinces in quadrant I, although their consumption water footprint exceeded the RFB, i.e., a water resource deficit, the imported surplus in these provinces was sufficient to overcome this deficit (WRTD > |WRD|). As a result, water resource in these provinces was kept intact as a result of the utilization of external water. The seven provinces in quadrant II, whose consumption water footprint was within their RFBs, i.e., had a water resource remainder, were also net virtual water importers. In these provinces, water resource was replenished through moderate use of local water while also benefiting from external water input. We identified four provinces in quadrant III, whose net virtual water exports did not exceed their water resource remainder (|WRTD| < WRD); the water resource of these provinces was therefore intact or replenished.

The effects of trade and final consumption also showed different patterns in the provinces, which exceeded their RFBs, i.e., the provinces located in quadrants IV, V, and VI. For the three provinces in quadrant IV, their net virtual water exports exceeded the water resource remainder (|WRTD| > WRD). The water resource of these provinces was found to be depleting as a result of their large exports. Provinces in quadrant V were also in a state of water resource deficit, which, coupled with being net virtual water exporters, comprised the worst-case scenario among all quadrants. The water scarcity situation was aggravated by the large final demand both within and beyond the administrative areas of these provinces. For the nine provinces in quadrant VI, the net imports of these provinces were smaller than their water resource deficit (WRTD < |WRD|). The water resource of these provinces was therefore depleting as a result of their large final demand and correspondingly low RFB.

Relationship between Trade and the Water Sustainability Gap. Our results show that being a net virtual water importer or exporter does not in itself determine whether the water withdrawal of a region exceeds its RFB. However, we found that provinces showed varied virtual water trade patterns depending upon whether their water withdrawal can support local consumption or production (Figure 2b). Two indicators are thus proposed to investigate such differences (SI Note 1 of the Supporting Information). The dependency index reveals the extent to which provinces rely on virtual water imports to fulfill their final consumption demand. We found that provinces with a consumption water footprint exceeding their RFBs (water resource deficit) relied more on virtual water imports, i.e., had a higher dependency index (panels a and b of Figure 3). This might be because the limited local water resource of these provinces is unable to meet the large final consumption demand, and the province must therefore rely on virtual water imports. As seen in Figure 3a, most provinces with a higher dependency index are in north China, which is known to be water-scarce. In contrast, the contribution index reveals the extent to which the provinces use their local water for virtual water exports. We found that provinces with water withdrawals exceeding their RFBs used more of their water withdrawal for virtual water exports, i.e., had a higher contribution index (panels c and d of Figure 3). Such results indicate virtual water exports contribute significantly to RFB exceedance in these provinces. Similarly, provinces with a higher contribution index are located in north China (Figure 3c).

In general, our findings suggest water-stressed provinces in north China mitigate their water stress through importation of virtual water from other water-stressed provinces, thus contributing to RFB exceedance in these exporting provinces. Indeed, for the provinces in quadrant VI, which were net virtual water importers and in RFB exceedance, 78% of their imported goods and services came from other RFB exceeding provinces. These imports were mainly used to fulfill the final demands of the "agriculture", "food processing and tobacco", and "chemical industry" sectors, while the water withdrawal embodied in the exporting provinces mainly came from the "agriculture", "chemical industry", and "textiles" sectors.

Potential for Trade To Reverse Regional Freshwater Boundary Exceedance. Given that provinces are interlinked through trade, importing more virtual water may reverse RFB exceedance for importing provinces but further jeopardize water resources of water-scarce exporting provinces. Our scenarios were thus designed to investigate this dilemma (Table 1). We deemed provinces in quadrant VI to be the most promising for reversing RFB exceedance by increasing imports because these provinces were net virtual water importers among the provinces exceeding the RFB. As for the provinces in quadrants IV and V, they exceeded their RFBs but were net virtual water exporters. For large virtual water exporters in these two quadrants, such as Jiangsu, Xinjiang, and Heilongjiang, increasing their imports is unlikely to offset the effect of their exports in terms of RFB exceedance. While for small virtual water exporters, such as Hubei and Jilin, increasing their imports may reverse their RFB exceedance, i.e., by changing these provinces from net exporters to net importers. Such a transition may be difficult to realize, requiring fundamental economic restructuring of these provinces.[48,49]

Table 1. Scenarios Developed To Explore Trade Potential for Water Sustainability Gap Reduction

scenarios	description
1	expanding imports of quadrant VI provinces under current trade patterns; assuming all final demand of provinces in quadrant VI are to be met through imports
2	allowing quadrant VI provinces only to increase imports from net virtual water exporters with no RFB exceedance, i.e., quadrant III provinces
3	(i) allowing quadrant VI provinces only to increase imports from net virtual water exporters with no RFB exceedance, i.e., quadrant III provinces; (ii) further reducing water intensity in all provinces

Hence, we started by assuming that all final demands of provinces in quadrant VI were to be met through import rather than local production. The following scenarios illustrate different strategies to help balance RFB exceedance of both importers and exporters (Table 1). The allocation of increased imports was based on existing trade patterns using the proportional method (SI Note 1 of the Supporting Information). More details relating to sectoral water intensity adjustment in scenario 3 can be found in SI Note 1 of the Supporting Information.

We found that expanding imports of quadrant VI provinces under current trade patterns (scenario 1) could save 37.6 km^3 of local water withdrawal, resulting in a 47% reduction in RFB exceedance. Two provinces (Shanxi and Liaoning) in this quadrant would fall back within their RFBs. However, such water savings would come at the cost of greater water withdrawal, i.e., 133.3 km^3 to virtual water exporters in other quadrants. Such a significant increase in water withdrawal would turn China into a national-level freshwater boundary exceeding the country by 48.6 km^3 exceedance. The provinces experiencing RFB exceedance in quadrants IV and V are the major virtual water exporters to provinces in quadrant VI. These provinces would experience an increase in virtual water exports of 94.7 km^3, resulting in a saving of just 22.4 km^3 water in quadrant VI. It should be noted that scenario 1 was intended to provide an extreme case through investigating the maximum potential of increased imports in reversing exceedances in quadrant VI provinces. The scenario analysis revealed that even relying on increased imports to the greatest extent would be insufficient to reverse RFB exceedances in most importing provinces.

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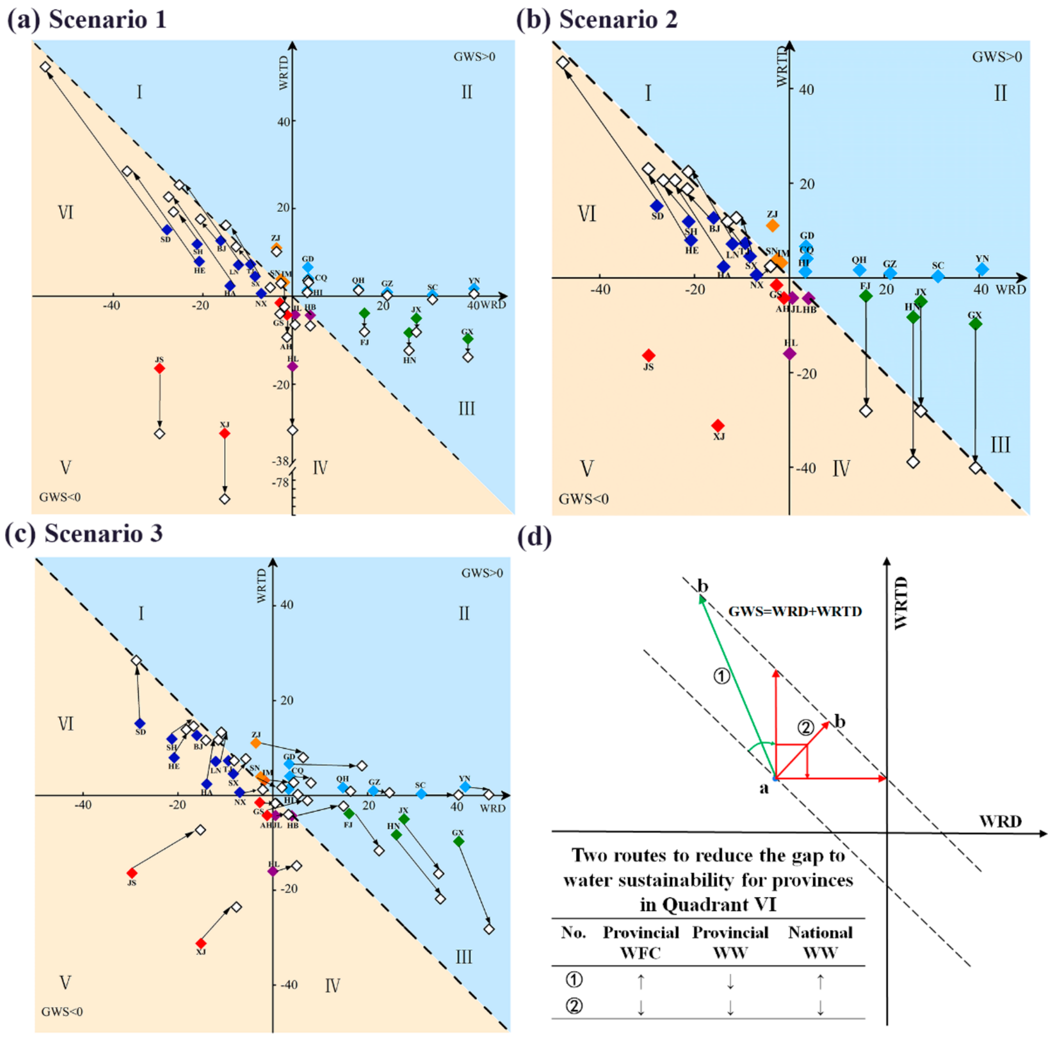

Figure 4. Potential for trade to reduce provincial-level RFB exceedance under (a) scenario 1, expanding imports of quadrant VI provinces under current trade patterns, (b) scenario 2, expanding imports of quadrant VI provinces only from quadrant III provinces, and (c) scenario 3, further reducing water intensity based on scenario 2. The colored diamonds indicate the current state of each province, and the white diamonds are the changed state under different scenarios. Panel d represents two different routes to reverse RFB exceedance for provinces in quadrant VI (WW, water withdrawal; WFC, water footprint consumption).

A second possibility, scenario 2, would be to incentivize provinces in quadrant VI to increase imports from provinces not exceeding their RFBs, but which are net virtual water exporters, i.e., quadrant III provinces. This scenario would exploit the potential for provinces supplying virtual water but who do not exceed their RFBs, meanwhile avoiding overuse of water resources in provinces already in RFB exceedance. However, the expansion of virtual water exports would result in all quadrant III provinces exceeding their RFBs, resulting in a 26.0 km^3 water resource overshoot. Only two provinces in quadrant VI, i.e., Shanxi and Liaoning, would reverse their RFB exceedances. Overall, supplementing water resource in quadrant VI provinces (45.5 km^3) would result in quadrant III provinces increasing their water withdrawal for virtual water export by 108.3 km^3, again tipping the whole of China into national freshwater boundary exceedance (by 23.6 km^3).

Our analysis of scenarios 1 and 2 suggests that resorting only to interprovincial trade expansion to close the provincial-level water sustainability gap may serve only to widen the gap at the national level. The underlying cause for this is that more water will be consumed if provinces in quadrant VI choose to import goods and services rather than producing their own, because provinces in quadrant VI generally have a lower water intensity than virtual water exporting provinces (Table S3 of the Supporting Information). As a result, both the consumption water footprint and water resource deficit for quadrant VI provinces will increase, making the route to regaining the RFB inefficiently longer (route ① in Figure 4d). In contrast, route ② offers a shorter and more efficient path toward narrowing the gap to water sustainability for quadrant VI provinces. Provinces moving along route ② will also reduce national-level water withdrawal as a result of lower water intensity in exporting provinces. Both routes ① and ② highlight the importance of considering differences in water intensity between trading partners. We thus propose scenario 3, i.e., increasing virtual water imports from quadrant III provinces while reducing water intensity for all provinces.

Scenario 3 does indeed show better results when it comes to narrowing the gap to water sustainability at both the provincial and national levels. Provinces in quadrant VI would reduce the gap to water sustainability from 66.8 to 10.8 km^3 RFB exceedance. Three provinces (Shanxi, Liaoning, and Henan) in quadrant VI would reverse their RFB exceedances. It is worth noting that reducing water intensity on its own would have a limited effect on quadrant VI provinces, reversing their RFB exceedances (SI Note 1 of the Supporting Information). This is because existing lower water intensities in these provinces leave limited scope for further gains (Table S3 of the Supporting Information). Meanwhile, all provinces in quadrant III would operate within their RFBs as a result of water intensity reduction, despite their expanded net virtual water exports by 158−226%. In addition, water intensity reduction would narrow the gap to water sustainability for provinces in quadrants IV and V, alleviating RFB exceedance from 121.9 to 65.4 km^3. Anhui and Hubei provinces in quadrants IV and V would reverse their RFB exceedances altogether, being 19.0 km^3 within their RFBs.

■ DISCUSSION

We proposed a new framework that describes the local features of the RFB involving trade impacts. Such a framework may also be used for other planetary boundary processes, which have spatially heterogeneous control variables, such as phosphorus and nitrogen cycles and land-system change. In contrast to previous work, we compared regional water withdrawal with RFB using a bottom-up approach and further differentiated the impact of both virtual water import and export to the changes in the gap to water sustainability. The impact of exports in our framework may be directly depicted by differentiating water withdrawal to internal water footprint and water use for exports (Figure S1 of the Supporting Information). The influence of imports is indirect; the reduction of local water withdrawal can, to some extent, be realized by substituting local production with imports. However, it should be noted that increasing imports may make a negligible contribution to reducing local water withdrawal. This may occur when the increased imports are used to meet increased final demand and, thus, not able to substitute local production (Figure S6 of the Supporting Information). Increasing imports may therefore only make a minor contribution to reducing RFB exceedance but make importers more reliant on external water resource. Our framework is also subject to a number of limitations and uncertainty results, which may be improved through data refinement and expansion to include different sources of water, such as surface water, groundwater, and soil moisture (SI Note 2 of the Supporting Information).

Our framework illustrates the possible choices in adjusting trade to reverse RFB exceedance through the six-quadrant approach. The case study shows that trade played a limited role in reversing the exceedance of China's provincial-level RFB. First, relying on trade to reduce water withdrawal may not be applicable to all provinces. For net virtual water exporters, although it seems a promising opportunity to decrease exports to reduce local water withdrawal for them, such action would carry high socio-economic consequences, such as reductions in household income and local employment, endangering national food security, especially in "breadbasket" provinces, such as Heilongjiang.[50,51] It would be even more challenging for these provinces to change from net virtual water exporters to net virtual water importers in the short term, requiring a fundamental economic restructuring. Second, although the net importing provinces with RFB exceedances may bear less cost in import expansion, only a small number of these provinces would reverse their RFB exceedances even by substituting all of their internal water footprints to virtual water imports. Hence, the provinces exceeding their RFBs need in-depth analysis to consider both the benefits to water resources and the relevant socio-economic costs in adjusting trade strategies.

The limited role played by trade can be explained by the unsustainable trade patterns within China, which are derived from two aspects. First, under current trade patterns, the mitigation of RFB exceedance through import expansion will endanger the water sustainability of the exporting provinces. Indeed, 69% of virtual water flow into quadrant VI provinces was imported from other provinces experiencing RFB exceedance. Second, differences in water intensity by province can affect the performance of trade strategy in reversing RFB exceedances. The expansion of imports from non-RFB exceeding exporters (quadrant III provinces) would result in them using more water to produce the exported goods and services than the importers, thus resulting in a RFB exceedance for these provinces. This is mainly due to their higher water intensities. The higher water intensity might be because these provinces lack investment support as a result of their less developed economies. Indeed, the per capita GDP of most of these provinces is lower than the provincial average[52] (Table S3 of the Supporting Information). In addition, the abundance of water resources in these provinces may result in fewer incentives to achieve lower water intensity. Hence, reducing water intensity while increasing virtual water exports from quadrant III provinces is promising to reverse unsustainable trade patterns in China. Because the factor of trade distance was considered in our scenario setting (SI Note 1 of the Supporting Information), increased imports will come from nearby provinces rather than from remote provinces when the exporting provinces have a similar economic output. Hence, such a suggested trade adjustment would also reduce the time, labor, transportation, and energy consumption costs associated with long-distance trade. It should be noted that reducing water intensity alone (SI Note 1 of the Supporting Information) or in combination with trade strategies would be insufficient to reverse RFB exceedances in most provinces. Other methods, such as desalination, interbasin water transfer, rainwater harvesting, and reclaimed water, may further help alleviate regional water crises.[7,53,54] However, comparing or combining the effects of these methods with trade strategies or water intensity reduction to reverse RFB exceedances is beyond the scope of this study.

Our case showed that provincial actions related to trade may have national consequences. Accordingly, avoiding RFB exceedance will help retain a global safe operating space for freshwater.[6] The global freshwater boundary situation may deteriorate if a region with RFB exceedance expands imports from other regions that transgress their RFBs and have a higher water intensity. Conversely, reducing water intensity of exported goods and services will help reduce freshwater boundary exceedance at both the local and global scales. Assessing the sustainability of international trade links from a water-saving perspective may thus be identified through the links that can mitigate freshwater boundary exceedance at the global scale. Both importers and exporters need to be aware of both the global and regional impacts of their trading actions on the freshwater boundary exceedance. Our framework and assessment tools can readily be used to evaluate the sustainability of such trade links. To reduce the negative global impacts of trade, it is important to build the mechanisms of responsibility, sharing, and cooperation between trading partners.

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ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c01699.

Detailed information on the regional freshwater boundary estimation, provincial exceedance rate, dependency and contribution index, scenario setting, limitations and uncertainty analysis, figures of the freshwater boundary at the provincial level, freshwater boundary per capita at the provincial level, contribution of different economic sectors to total gap to water sustainability in China, system boundaries of our research, and zero contribution of increasing imports to water withdrawal reduction, and tables of the gap to water sustainability of 30 Chinese provinces, water intensity of 30 Chinese provinces in 2015, increased rate of irrigation efficiency and decreased rate of industrial water intensity in 30 Chinese provinces, and uncertainties of this study (PDF)

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Notes

The authors declare no competing financial interest.

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