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Spatial Mismatch Between Agricultural Water Withdrawal and Agricultural-Stage Value Added Attributed to Selected Household Demand in China

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Abstract

Household agri-food-related demand links consuming provinces to agricultural water withdrawal at distant production origins, but withdrawal and agricultural-stage value added may have different production geographies. Using China's 2020 provincial multi-regional input–output table, we attributed both accounts to rural and urban household final demand for the Agriculture, Forestry, Animal Husbandry and Fishery and Food and Tobacco Processing sectors. This sector-based proxy does not cover all household food consumption. Value added was measured at the agricultural production stage; Aqueduct baseline water stress characterized production origins without entering the mismatch calculation. Thirteen of the 31 provinces had negative value-added-minus-water share differences, led by Xinjiang (−11.55 percentage points). High and Extremely High stress provinces accounted for 65.95% of the national negative-mismatch magnitude, largely driven by Xinjiang; negative differences also occurred in lower-stress provinces. Xinjiang retained the most negative difference in the withdrawal-allocation sensitivity test, although some provincial signs changed. The framework identifies producer–consumer links for closer assessment of production-origin water conditions while distinguishing spatial accounting differences from production inefficiency or inequitable exchange.

Keywords: multi-regional input–output analysis; household final demand; agricultural water withdrawal; agricultural-stage value added; spatial mismatch; baseline water stress

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1. Introduction

Household final demand in agri-food-related sectors can induce agricultural production and water withdrawal outside the province where that demand is recorded. This producer–consumer separation matters in China, where consumption centers, agricultural production, and water resources are unevenly distributed. Previous studies have traced agri-food demand to blue-water pressure and interprovincial dietary-water transfers [1,2], while related work has mapped agricultural resource flows and production–consumption water accounts [3,4]. These spatial linkages require distinguishing the province where household demand is recorded from the province where the associated agricultural production and water withdrawal occur.

In volumetric water-footprint accounting, a water footprint includes water consumed and a pollution-related component along a production chain. Blue water denotes surface

water and groundwater; the blue-water footprint measures their consumptive use. Green water is precipitation stored in soil and used by vegetation, while the gray-water footprint expresses the dilution volume required to meet water-quality standards. Virtual-water flows link water used in production with traded goods and services, rather than physical transfers of that water [2]. The present study measures agricultural withdrawal, which includes water that may subsequently return to the hydrological system; it does not estimate a combined blue, green, and gray water footprint.

Food-related water demand has been examined through dietary, product-specific, and trade-based accounting frameworks. Studies of urban–rural dietary footprints and virtual-water transfers span provincial, city, and river-basin scales [2,5–7]. More disaggregated analyses examine individual food products, dietary transitions, pollution-related water scarcity, and pressures in producing basins [8–10]. Grain-trade and water–energy–food studies identify water pressures along specific commodity and sectoral pathways [11,12]. Their metrics and boundaries vary, making it important to distinguish product-level or scarcity-weighted footprints from a demand-attributed account constructed using reported provincial agricultural water withdrawal.

Related studies compare water use with economic value in interregional exchange. Zheng et al. [13] and Wei et al. [14] examined virtual-water and value-added transfers, whereas Cui et al. [15] considered net water–value positions and trade-related risks. Crop- and agriculture-focused studies have investigated value-chain decomposition, resource–economic trade-offs in coastal regions, and tensions among efficiency, sustainability, and equity [16–18]. Wei et al. [19] showed that global-value-chain accounting can alter the interpretation of virtual-water inequality. Wang et al. [20] found that aggregate water savings from crop trade can coexist with uneven distributions of water value. These studies establish that water use and economic value can follow different provincial patterns, but their net-flow, value-chain, and crop-level measures answer different questions from a matched comparison at the agricultural production stage.

Water use, economic value, and water stress have also been examined jointly. Wei et al. [21] combined provincial water withdrawal, scarcity, and value added in a responsibility indicator for China, while Zheng et al. [22] examined water, economic value, and hydrological stress across Chinese cities. Trade in agricultural and energy products has been linked to intensified water pressure in northern production bases [23], and Wang et al. [12] used Aqueduct classes to identify high-pressure trade pathways. These studies motivate examining the long-term water-stress context of production origins alongside the water and value accounts.

The remaining accounting question is how agricultural water withdrawal and agricultural-stage value added are distributed when both are attributed to the same selected household-demand and production origins. The comparison requires consistent demand definitions, water measures, and economic-stage boundaries. Such alignment matters because agricultural withdrawal occurs at the primary production stage, while value added across the wider supply chain spans several stages.

We address these questions using China's 2020 provincial multi-regional input–output (MRIO) table, covering 31 provinces and 42 sectors. Rural and urban household final demand for the Agriculture, Forestry, Animal Husbandry and Fishery sector and the Food and Tobacco Processing sector provides a broad sector-based proxy for selected agri-food-related consumption, not a product-specific account of all food consumption. Two research questions guide the analysis: (1) How are the two accounts attributable to selected household demand distributed across consuming and producing provinces? (2) Where do their production-side shares diverge, and how are the resulting differences distributed across baseline water-stress classes?

2. Materials and Methods

2.1. Research Framework

This study develops a provincial multi-regional input–output (MRIO) framework to examine the spatial distributions of agricultural water withdrawal and agricultural-stage value added attributable to selected household agri-food-related final demand in China. The analysis asks whether the two accounts have similar national production-side shares across producing provinces.

MRIO analysis is used because interprovincial and intersectoral transactions connect household demand to agricultural production through both direct purchases and upstream inputs. It preserves production origins while attributing water withdrawal and value added to the same demand. Comparing normalized provincial shares makes the physical and monetary accounts comparable without adding unlike units. This design addresses spatial attribution and accounting differences, rather than estimating behavioral responses or causal policy effects.

Aqueduct water stress provides long-term production-origin context and does not enter the calculation of attributed water withdrawal or spatial mismatch. Figure 1 summarizes the four-step analytical sequence.

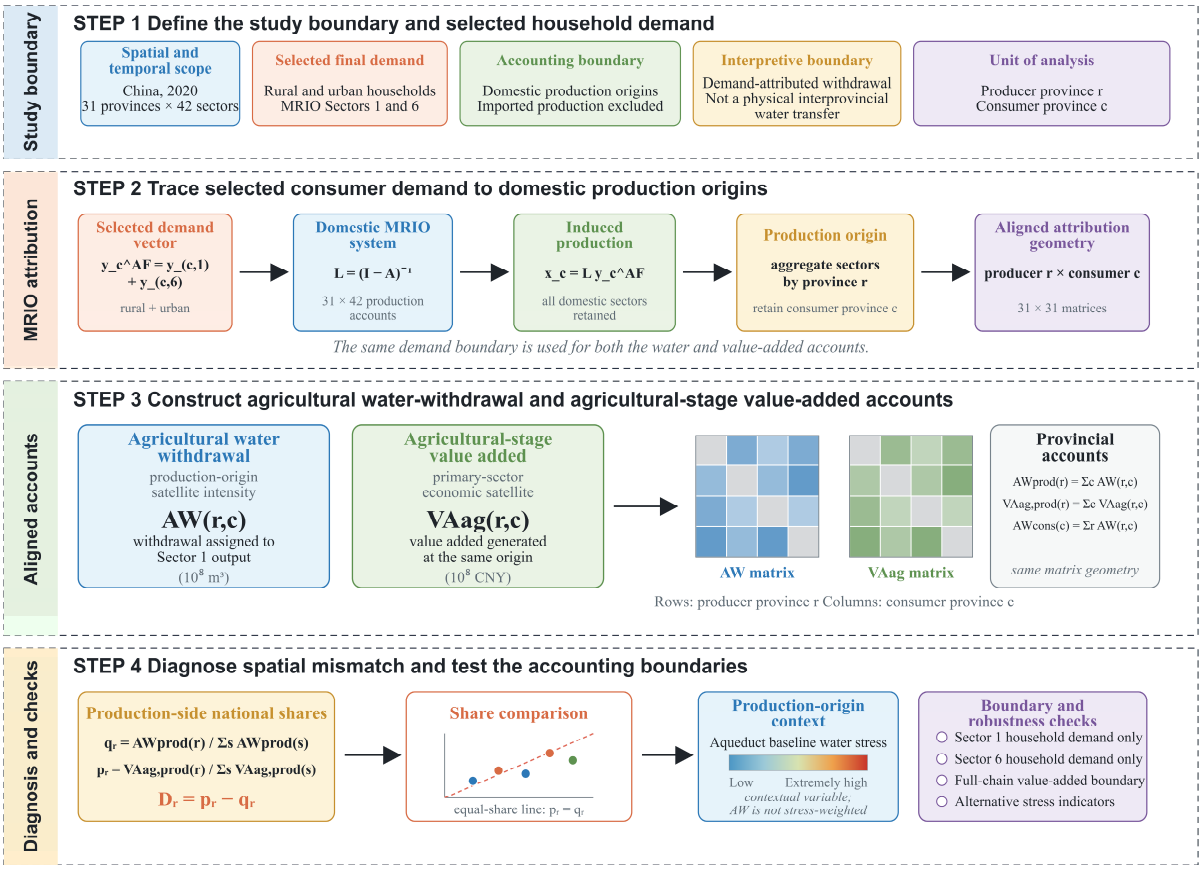

Figure 1. Analytical framework for demand-attributed agricultural water-withdrawal and agricultural-stage value-added accounting. Step 1 defines the spatial, temporal, and selected household-demand boundaries. Step 2 traces that demand through the domestic MRIO system to production origins. Step 3 constructs aligned producer–consumer agricultural water-withdrawal and agricultural-stage value-added accounts. Step 4 compares production-side shares and examines the resulting differences in the context of baseline water stress and boundary checks. Different colors distinguish the components of the analytical framework, while dashed outlines separate the four main analytical steps. The color gradient in Step 4 indicates the range of baseline water stress from low to extremely high. An additional withdrawal-allocation sensitivity test is described in Section 2.8.

2.2. Provincial Multi-Regional Input–Output Model

The economic analysis is based on the 2020 China provincial multi-regional input–output (MRIO) table, which covers 31 provincial-level regions and 42 sectors in each region, yielding 1302 province–sector accounts. The source workbook identifies CEADs as the data source. Its structure corresponds to the 2020 MRIO described by Li et al. [24] and archived in the dataset [25]. The system contains the intermediate transaction matrix, final-demand matrix, gross output vector, value-added accounts, and separately recorded imported intermediate content. Monetary values in the source table are expressed in 10^4 CNY. We use 2020, the later of the two years in the cited 2018/2020 MRIO release, to align the economic accounts with provincial agricultural withdrawal and population statistics for the same year. This provides a common accounting benchmark; it does not establish that 2020 represents typical conditions in other years. The main data sources, accounting boundaries, and analytical roles are summarized in Table 1.

Table 1. Main data sources, accounting boundaries, and analytical roles.

Account	Coverage	Source	Use	Boundary or Limitation
Provincial MRIO	2020; 31 provinces × 42 sectors	CEADs workbook and data descriptor [24,25]	Leontief attribution	Domestic production; selected household final demand
Household final demand	Rural and urban; Sectors 1 + 6	2020 MRIO final-demand matrix [25]	Demand vector by consuming province	Sector-based proxy; not complete household food consumption
Agricultural withdrawal	Province; Sector 1 direct account	China Water Resources Bulletin 2020 [26]	Water extension	Withdrawal; not consumptive use or a scarcity-weighted footprint
Agricultural-stage VA	Province; Sector 1	2020 MRIO VA and output [25]	Primary economic account	Matched agricultural stage; not producer income or welfare
Full-chain VA	Province; all 42 sectors	2020 MRIO VA and output	Boundary sensitivity	Not the primary matched-stage account
Aqueduct *bws*/*Tot*	Province; long-run 1979–2019	WRI Aqueduct 4.0 [27]	Production-origin context	Long-run production-origin context; not 2020 site-specific stress
Aqueduct bws/Irr	Province; irrigation weighting	WRI Aqueduct 4.0 [27]	Stress-context sensitivity	Same indicator family
2020 water-use-to-water-resources ratio	2020; provincial total water use/resources	China Water Resources Bulletin 2020 [26] (Tables 5 and 7 therein)	Annual consistency check	Annual descriptive ratio; not equivalent to Aqueduct

Note: VA denotes value added; bws denotes baseline water stress; *bws*/*Tot* and bws/Irr use total gross withdrawal and irrigation gross withdrawal as aggregation weights, respectively.

Let Z denote the 1302 × 1302 intermediate transaction matrix and x the corresponding gross output vector. The technical-coefficient matrix is calculated as

$$A = Z\hat{x}^{-1} \quad (1)$$

Here $\hat{x}$ is the diagonal matrix of gross output. Its diagonal generalized inverse has entry $\frac{1}{x_i}$ when $x_i > 0$ and zero when $x_i = 0$. The source table contains 27 zero-output province–sector accounts. For these accounts, the corresponding columns of A and the direct water and value-added coefficients defined below are set to zero. The Leontief inverse is then calculated as

$$L = (I - A)^{-1} \tag{2}$$

For a generic final-demand vector y_c associated with consuming province c, total output throughout the domestic production system attributable to that demand is

$$x_c = Ly_c \tag{3}$$

This formulation links final demand recorded in province c to production both within that province and elsewhere in China through direct and indirect intersectoral requirements. All calculations retain the original 31-region, 42-sector structure; province–sector accounts are not aggregated before application of the Leontief inverse. Section 2.3 defines the selected household final-demand vector used in the analysis.

The MRIO records imported intermediate content but does not identify foreign producing regions or their agricultural water and value-added intensities. Foreign production is therefore outside the attributed water and value-added accounts reported here. The results represent domestic production requirements associated with the selected final-demand boundary, rather than a complete global consumption footprint. Table 2 summarizes the core notation, dimensions, and definitions used in the analysis.

Table 2. Core notation, dimensions, and definitions.

Symbol	Dimension	Definition
Z	1302×1302	Intermediate transaction matrix
x	1302×1	Gross output vector
A	1302×1302	Technical-coefficient matrix
L	1302×1302	Leontief inverse
y_c^{AF}	1302×1	Selected household demand of consuming province c
w_i	Scalar	Direct agricultural-withdrawal intensity of account i
$AW_{r,c}$	Scalar	Withdrawal in producer r attributable to demand in c
v_i	Scalar	Direct value-added coefficient of account i
$VA_{r,c}^{\mathrm{ag}}$	Scalar	Agricultural-stage VA in r attributable to demand in c
p_r	Share	National agricultural-stage VA share of producer r
q_r	Share	National attributed-withdrawal share of producer r
D_r	Dimensionless share difference	Producer share difference $p_r - q_r$
M_r	Share magnitude	Negative-mismatch magnitude $\max(-D_r, 0)$

Note: AW denotes agricultural water withdrawal; superscript ag denotes the agricultural production stage.

2.3. Selected Household Agri-Food-Related Final Demand

The analysis selects rural and urban household final demand associated with two sectors in the 42-sector MRIO classification: (1) Agriculture, Forestry, Animal Husbandry and Fishery (Sector 1) and (2) Food and Tobacco Processing (Sector 6). For each consuming province c, the selected household final-demand vector is defined as

$$y_c^{\mathrm{AF}} = y_{c,1}^{\mathrm{R}} + y_{c,1}^{\mathrm{U}} + y_{c,6}^{\mathrm{R}} + y_{c,6}^{\mathrm{U}} \tag{4}$$

Here R and U denote the rural and urban household final-demand columns, respectively. Each term on the right-hand side is a 1302-element vector that retains entries for the

specified sector across all 31 producing provinces in the household final-demand column of the consuming province c, with all other entries set to zero. The sectoral restriction applies only to final demand; all 42 production sectors remain in A and L.

The rural and urban household-demand vectors are also retained separately as $y_{c,h}^{\mathrm{AF}} = y_{c,1}^{h} + y_{c,6}^{h}$ for $h \in \{\mathrm{R}, \mathrm{U}\}$. Producer–consumer agricultural water-withdrawal and agricultural-stage value-added accounts are first calculated for each household group and then summed across the two groups.

Here, "selected" refers to sector entries retained in the MRIO household final-demand columns, not to a sample of households. Both rural and urban household columns are included for all 31 provinces; no household-level sampling is undertaken. Household demand is the focus because the study traces consumption-related production requirements, with government demand, capital formation, inventory changes, and exports outside the selected final-demand vector. The term selected household agri-food-related final demand reflects the sectoral boundary: Sector 1 includes non-food activities, and Sector 6 includes tobacco. Accommodation and catering form one sector and cannot be separated reliably, so this combined sector is excluded. These mixed activities are not artificially split or treated as missing observations.

To assess sensitivity to the selected sectors, two alternative final-demand boundaries are considered: household final demand for Sector 1 only and household final demand for Sector 6 only.

For the supporting urban–rural per capita comparison, the urban population of province c is estimated as $N_{c,U} = N_c u_c$ and the rural population as $N_{c,R} = N_c(1 - u_c)$, where N_c is the 2020 year-end population and u_c is the 2020 urban population share reported in the China Statistical Yearbook 2021 [28]. Group-specific consumption-side attributed agricultural water withdrawal and agricultural-stage value added are divided by the corresponding estimated populations, with the source units converted to m^3 per person and CNY per person. These are demand-attributed per capita measures; they do not represent direct household water use or individual food intake. Population and urbanization inputs are available for all 31 provinces; year-end populations serve as proxies for the population denominators of annual flows.

To interpret the urban–rural difference, per capita attributed withdrawal is expressed as the product of selected final-demand expenditure per person and attributed withdrawal per unit of that expenditure. The latter combines the sectoral and production-origin composition of demand with the fixed MRIO production requirements and water coefficients. National group values use summed expenditure, attributed withdrawal, and population, rather than unweighted provincial averages. This accounting identity does not isolate behavioral causes; Supplementary Material S2 reports the calculations.

2.4. Agricultural Water-Withdrawal Account

Provincial agricultural water-withdrawal data for 2020 are obtained from Table 7 of the China Water Resources Bulletin 2020 [26]. The bulletin's water-use figures describe water taken for off-channel uses, including conveyance losses; they are treated here as withdrawal rather than consumptive use. The 31 published provincial agricultural values, reported in 10^8 m^3, sum to 3612.5×10^8 m^3, compared with the separately reported national total of 3612.4×10^8 m^3. The resulting 0.1×10^8 m^3 rounding difference is retained and is not redistributed across provinces. Agricultural-withdrawal values are available for all 31 provinces; no missing provincial withdrawal values are imputed. A harmonized agricultural consumptive-use account for all 31 provinces was unavailable in the assembled data. Withdrawal was therefore retained as the water measure, without converting it to consumptive use through assumed consumption rates.

The provincial MRIO represents agriculture, forestry, animal husbandry, and fishery as one aggregated sector (Sector 1). Each province's reported agricultural water withdrawal is assigned to Sector 1 of that province, while direct agricultural water withdrawal for its remaining 41 sectors is set to zero. This mapping yields a 1302-element direct agricultural water-withdrawal vector E^{AW}.

The direct agricultural water-withdrawal intensity of province–sector account i is calculated as

$$w_i = \frac{E_i^{\mathrm{AW}}}{x_i} \tag{5}$$

For the selected household final demand of consuming province c, agricultural water withdrawal attributable to that demand across the domestic production system is calculated as

$$AW_c = \hat{w} L y_c^{\mathrm{AF}} \tag{6}$$

where $\hat{w}$ is the diagonal matrix of direct agricultural water-withdrawal intensities.

To retain the production origin, attributed elements belonging to producing province r are aggregated as

$$AW_{r,c} = \sum_{i \in r} w_i \left[L y_c^{\mathrm{AF}} \right]_i \tag{7}$$

Because direct agricultural water withdrawal is assigned only to Sector 1, $AW_{r,c}$ represents agricultural water withdrawal occurring in producing province r and attributable to the selected household final demand of consuming province c.

The mapping uses 31 province-specific agricultural water-withdrawal intensities, each applied uniformly to Sector 1 output within its province. The zero entries for the other sectors define the agricultural-withdrawal boundary; they do not represent missing observations or imply that those sectors use no water. Provincial totals are taken directly from the bulletin, rather than allocated from the national total using area weights. Differences among crops, irrigation systems, and locations within a province remain unresolved. Attributed agricultural water withdrawal is reported in 10^8 m^3.

The resulting 31 × 31 producer–consumer matrix distinguishes the location of agricultural water withdrawal from the location of the household final demand to which it is attributed. For consuming province c, the column sum

$$AW_c^{\mathrm{cons}} = \sum_r AW_{r,c} \tag{8}$$

gives agricultural water withdrawal across all producing provinces attributable to its selected household final demand. For producing province r, the row sum

$$AW_r^{\mathrm{prod}} = \sum_c AW_{r,c} \tag{9}$$

gives agricultural water withdrawal occurring in that province and attributable to the selected household final demand of all 31 consuming provinces.

Both totals are conditional on the selected household final-demand boundary defined in Section 2.3. The production-side total represents only the corresponding attributed portion of the producing province's reported agricultural water withdrawal; the consumption-side total is not a portion of the consuming province's own reported withdrawal.

2.5. Agricultural-Stage Value-Added Accounting

Value added is derived from the value-added accounts of the same 2020 provincial MRIO table. For province–sector account i, the direct value-added coefficient is calculated as

$$v_i = \frac{VA_i}{x_i} \tag{10}$$

where VA_i denotes direct value added and the denominator is gross output.

To align the economic account with the production-stage boundary of agricultural water withdrawal, the primary analysis includes value added generated in Sector 1 only. Agricultural-stage value added generated in producing province r and attributable to the selected household final demand of consuming province c is calculated as

$$VA_{r,c}^{\mathrm{ag}} = v_{r,1}\left[Ly_c^{\mathrm{AF}}\right]_{r,1} \tag{11}$$

For consuming province c, the corresponding consumption-side total is

$$VA_c^{\mathrm{ag,cons}} = \sum_r VA_{r,c}^{\mathrm{ag}} \tag{12}$$

For producing province r, the corresponding production-side total is

$$VA_r^{\mathrm{ag,prod}} = \sum_c VA_{r,c}^{\mathrm{ag}} \tag{13}$$

Here, value added is limited to that generated at the agricultural production stage and attributable to the selected final-demand boundary. It is not producer income, profit, local welfare, or economic benefit retained by the producing province. Values are calculated in the MRIO source unit of 10^4 CNY and divided by 10^4 when reported in 10^8 CNY.

In the baseline, a province's agricultural withdrawal and agricultural-stage value added are calculated by multiplying the same attributed Sector 1 output by the respective direct coefficients. The attributed value-added-to-withdrawal ratio therefore equals the province's full Sector 1 value-added-to-withdrawal ratio. Demand determines the scale and destination of attributed output, while the fixed coefficients determine this within-origin ratio. Supplementary Material S2 uses these identities to interpret Xinjiang and Beijing without changing the baseline accounts.

As a sensitivity analysis of the economic-accounting boundary, full-chain value added is calculated as

$$VA_{r,c}^{\mathrm{full}} = \sum_{i \in r} v_i \left[Ly_c^{\mathrm{AF}}\right]_i \tag{14}$$

This account captures value added generated across all 42 domestic production sectors located in producing province r and attributable to the selected household final demand of consuming province c. The alternative changes the value-added accounting boundary while leaving the agricultural water-withdrawal account unchanged.

2.6. Measurement of Spatial Mismatch

Because agricultural water withdrawal and value added have different physical and monetary units, each account is normalized by its own national attributed total before provincial shares are compared. The primary analysis compares these production-side shares under the same selected household final-demand boundary.

For producing province r, the national production-side share of agricultural-stage value added is defined as

$$p_r = \frac{VA_r^{\mathrm{ag,prod}}}{\sum_r VA_r^{\mathrm{ag,prod}}} \tag{15}$$

and the corresponding national production-side share of agricultural water withdrawal is

$$q_r = \frac{AW_r^{\text{prod}}}{\sum_r AW_r^{\text{prod}}} \tag{16}$$

The producer-level share difference used to characterize spatial mismatch is defined as

$$D_r = p_r - q_r \tag{17}$$

A negative D_r indicates that province r accounts for a larger national share of attributed agricultural water withdrawal than of agricultural-stage value added, whereas a positive D_r indicates the reverse.

For reporting and graphical presentation, the share difference is expressed in percentage points:

$$D_r^{\text{pp}} = 100 D_r \tag{18}$$

Because the national production-side shares p_r and q_r each sum to unity,

$$\sum_r D_r = 0 \tag{19}$$

This measure is a descriptive comparison of two national spatial shares, rather than an inequality or equity index. Related water–land–food research has examined spatial mismatches between other resource-related accounts [29]. Here, D_r compares the national shares of agricultural-stage value added and attributed agricultural water withdrawal under the same final-demand boundary. A value of $D_r = 0$ denotes equal national shares; it does not by itself imply economic efficiency, environmental optimality, or social equity.

For graphical presentation, the corresponding 45° equal-share reference is defined by

$$p_r = q_r \tag{20}$$

This line represents equal national shares of the two production-side accounts.

The producer-level share difference can also be decomposed bilaterally by consuming province. For producing province r and consuming province c, the bilateral contribution is defined as

$$D_{r,c} = \frac{VA_{r,c}^{\text{ag}}}{\sum_{r,c} VA_{r,c}^{\text{ag}}} - \frac{AW_{r,c}}{\sum_{r,c} AW_{r,c}} \tag{21}$$

Summing $D_{r,c}$ over the 31 consuming provinces recovers D_r. For a given producer r with $AW_{r,c} > 0$, $\frac{VA_{r,c}^{\text{ag}}}{AW_{r,c}} = \frac{v_{r,1}}{w_{r,1}}$ for every c. Accordingly, bilateral differences locate the consumer-demand contributions to a producer-specific accounting relationship.

2.7. Baseline Water-Stress Context

To characterize the hydrological context of production origins, the 31 producing provinces are classified using WRI Aqueduct 4.0 province_baseline data for China (indicator: bws; weight: Tot, total gross withdrawal) [27]. These classes represent long-term baseline water-stress conditions for 1979–2019 rather than water stress measured at specific agricultural-withdrawal locations in 2020. Province names are matched explicitly to the 31 MRIO regions, and all regions are assigned an Aqueduct class. No provincial Aqueduct scores or classes are imputed.

The five named Aqueduct baseline water-stress classes are Low (<10%), Low–Medium (10–20%), Medium–High (20–40%), High (40–80%), and Extremely High (>80%). These

classes are taken directly from Aqueduct; its 0–5 risk score is not treated as a physical withdrawal-to-availability ratio.

Water-stress classes are assigned to producing province r rather than consuming province c. Negative-mismatch magnitudes are aggregated by these classes as defined below.

For each class g, attributed agricultural water withdrawal and agricultural-stage value added are summed across its producing provinces using AW_r^{prod} and $VA_r^{\text{ag,prod}}$ and divided by their respective national attributed totals. As a separate distributional benchmark, each stress class's share of the 31 published provincial agricultural water-withdrawal values is calculated using the bulletin values and their provincial sum. This benchmark remains distinct from demand-attributed agricultural water withdrawal.

For producing province r, the magnitude of a negative mismatch is defined as

$$M_r = \max(-D_r, 0) \tag{22}$$

For water-stress class g, its share of the national negative-mismatch magnitude is calculated as

$$S_g^M = \frac{\sum_{r \in g} M_r}{\sum_r M_r} \tag{23}$$

This aggregation describes where negative mismatches coincide with different baseline water-stress conditions; it does not imply that water stress causes the mismatch.

An additional link-level screen identifies cross-provincial producer–consumer pairs that simultaneously have (i) a producing province in Aqueduct's High or Extremely High class, (ii) $AW_{r,c}$ at or above the 90th percentile of AW among all 930 directed cross-provincial pairs for the same demand boundary, and (iii) $D_{r,c} < 0$. The percentile uses linear interpolation of ordered observations. Eligible pairs are ranked from the most negative $D_{r,c}$, with larger $AW_{r,c}$ breaking ties. The threshold is recalculated for each alternative final-demand boundary. This descriptive screen identifies coincident conditions; it is neither an ecological-damage measure nor an optimized policy priority list.

Aqueduct scores serve as production-origin water-stress context. They are not applied as continuous multipliers to agricultural water withdrawal or used to construct a scarcity-adjusted water footprint.

2.8. Design of Boundary and Robustness Checks

Four sets of checks examine sensitivity to the household final-demand boundary, the economic-accounting boundary, the representation of water-stress context, and within-province withdrawal allocation. The final-demand, economic-accounting, and withdrawal-allocation checks change an account used to calculate spatial mismatch. The water-stress check changes only the context assigned to producing provinces.

First, the primary Sector 1 + Sector 6 household final-demand boundary is compared with Sector 1-only and Sector 6-only alternatives. For each alternative, attributed agricultural water withdrawal, agricultural-stage value added, their national production-side shares, D_r, and the link-level screen are recalculated. The screen uses the 90th-percentile water-withdrawal threshold calculated for that final-demand boundary.

Second, agricultural-stage value added is replaced with value added generated across all 42 domestic production sectors, while agricultural water withdrawal remains unchanged. The corresponding full-chain share difference is defined as

$$D_r^{\text{full}} = \frac{VA_r^{\text{full}}}{\sum_r VA_r^{\text{full}}} - q_r \tag{24}$$

This comparison shows how the producer-level share difference depends on the economic-accounting boundary. A change from D_r to D_r^{full} does not indicate a change in agricultural production efficiency.

Third, two alternative representations of water-stress context are examined. The primary Aqueduct *bws*/*Tot* classification is compared with bws/Irr, an alternative weighting of the same baseline-water-stress indicator using irrigation gross withdrawal. Separately, a 2020 annual water-use-to-water-resources ratio is calculated from total water use in Bulletin Table 7 and total water resources in Table 5 [26]. This annual ratio is used as a descriptive consistency check. Its accounting period and water-use and hydrological boundaries differ from those of Aqueduct, so it is neither an equivalent measure of long-term baseline water stress nor a scarcity characterization factor. Values above 1 are retained.

Fourth, a deterministic allocation sensitivity test varies the effective water intensity of agricultural output attributed to the selected household demand by ±10% and ±20%, one producing province at a time (124 scenarios). Each province's reported total withdrawal is preserved by offsetting the allocation to its remaining agricultural output. All residual allocations are nonnegative. Final demand, the Leontief inverse, value-added coefficients, and water-stress classes remain fixed. Provincial share differences are recalculated using the revised national attributed-withdrawal denominator. We also calculate the intensity multiplier at which each province's share difference reaches zero, holding other provinces' allocations fixed. Supplementary Material S1 gives the equations, feasibility constraints, and results. The percentage changes are illustrative diagnostic settings, not empirical error bounds or estimated corrections for crop-level heterogeneity.

For the final-demand, economic-accounting, and withdrawal-allocation checks, the ranks and signs of provincial D_r values are compared with those under the primary specification, and Spearman rank correlations are reported. For the Aqueduct weighting check, provincial class membership, class-level shares of attributed agricultural water withdrawal, and class-level shares of national negative-mismatch magnitude are compared. The annual ratio is compared with the Aqueduct *bws*/*Tot* score using Spearman rank correlation. Water-stress representations do not enter the calculation of D_r; therefore, no D_r sign or rank comparison applies to these context checks.

To assess whether Xinjiang-origin links dominate the displayed link ranking, an additional display check removes those links from the eligible candidate list. Xinjiang's official water-withdrawal value, the national denominators, and the original 90th-percentile cutoff remain unchanged. The checks describe sensitivity to accounting boundaries, withdrawal allocation, and contextual classifications; they do not support causal interpretation.

3. Results

3.1. Consumption-Side Attribution of Agricultural Water Withdrawal and Agricultural-Stage Value Added

Across the 31 provinces, domestic agricultural water withdrawal and agricultural-stage value added attributable to the selected rural and urban household final demand totaled 1905.49 × 10^8 m^3 and 43,132.38 × 10^8 CNY, respectively. These totals cover the portions attributable to household final demand for Sectors 1 and 6, not total national agricultural water withdrawal or value added.

Consumption-attributed agricultural water withdrawal varied across provinces. Jiangsu had the largest total (approximately 187 × 10^8 m^3), followed by Guangdong (160 × 10^8 m^3) and Hunan (116 × 10^8 m^3). Fujian, Zhejiang, and Sichuan each exceeded 100 × 10^8 m^3. At the lower end, Beijing, Tianjin, Hainan, Tibet, Gansu, Qinghai, and Ningxia each had less than 20 × 10^8 m^3.

The nonlocal production share followed a different provincial pattern. Approximately 91% of the agricultural water withdrawal attributed to Beijing's selected household demand occurred outside the municipality, compared with about 80% for Shanghai, 79% for Zhejiang, 76% for Chongqing, and 75% for Shaanxi. Xinjiang had the lowest nonlocal share (about 9%), while Tibet and Ningxia were also below 20%. Thus, the scale of consumption-attributed withdrawal and reliance on production elsewhere did not move together: Beijing and Shanghai had relatively small attributed totals but high nonlocal shares.

Figure 2 maps the corresponding producer–consumer agricultural water-withdrawal links nationally and within the Yellow River and Yangtze River regions.

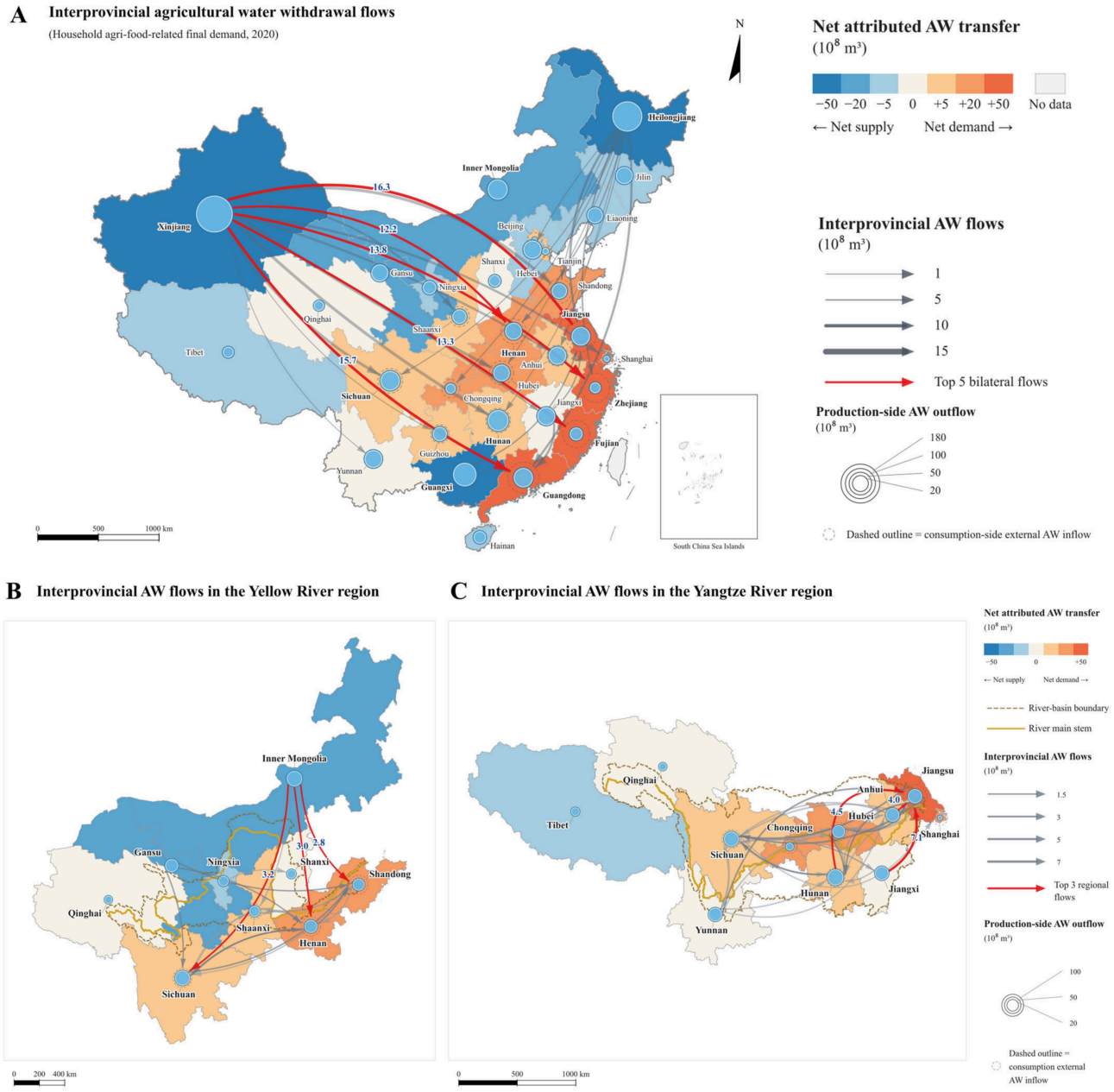

Figure 2. Interprovincial agricultural water-withdrawal flows in China and the Yellow River and Yangtze River regions. Panel (**A**) maps national net attributed agricultural water transfer and the principal producer-to-consumer flows. Panels (**B**,**C**) show the corresponding regional flow structures using complete provincial MRIO units. Arrow width represents attributed flow volume, node size represents production-side outflow, and red arrows identify the largest displayed links.

For Beijing, 15.24 × 10^8 m^3 of the 16.77 × 10^8 m^3 total occurred outside the municipality, leaving 1.52 × 10^8 m^3 locally. The nonlocal share was 80.63% when measured by attributed agricultural gross output at MRIO prices, compared with 90.92% for withdrawal. The higher water share reflects the larger average withdrawal coefficient of the nonlocal agricultural production attributed to Beijing's demand (Supplementary Material S2, Table S6).

Nationally, 52.81% of attributed agricultural water withdrawal and 49.28% of agricultural-stage value added occurred outside the consuming province. Jiangsu had the largest consumption-attributed agricultural-stage value-added total (approximately 3851 × 10^8 CNY), followed by Guangdong (3739 × 10^8 CNY), Shandong (2971 × 10^8 CNY), Henan (2964 × 10^8 CNY), and Sichuan (2875 × 10^8 CNY). Hunan ranked third for consumption-attributed withdrawal but sixth for agricultural-stage value added (2550 × 10^8 CNY). These value-added amounts were generated at agricultural production origins across China in response to each consuming province's selected household final demand. They do not represent value added retained by the consuming province.

Urban household demand was associated with 1346.03 × 10^8 m^3 of agricultural water withdrawal and 30,492.97 × 10^8 CNY of agricultural-stage value added, compared with 559.46 × 10^8 m^3 and 12,639.42 × 10^8 CNY, respectively, for rural household demand. Based on the estimated urban and rural populations, per capita attributed agricultural water withdrawal was 149.52 m^3 for urban residents and 109.72 m^3 for rural residents; the corresponding agricultural-stage value added was 3387.23 and 2478.82 CNY per person. Urban per capita attributed withdrawal exceeded the rural value in 26 of the 31 provinces. These demand-attributed measures follow the selected sectoral boundary; they do not represent direct household water use or consumption of identical food baskets.

National selected final-demand expenditure was 7071.10 CNY per urban resident and 4801.76 CNY per rural resident, a 47.26% difference. Attributed withdrawal per 10,000 CNY of this demand was lower for urban households (211.45 m^3) than for rural households (228.50 m^3), by 7.46%. The corresponding urban-to-rural ratios multiply to 1.3627, reproducing the 36.27% difference in per capita attributed withdrawal. The same 26 provinces with higher urban per capita withdrawal also had higher urban per capita selected expenditure; the five exceptions were Liaoning, Shanghai, Jiangsu, Zhejiang, and Guangdong (Supplementary Material S2, Tables S3 and S4).

3.2. Production-Side Distribution of Agricultural Water Withdrawal and Agricultural-Stage Value Added

The production-side distribution of attributed agricultural water withdrawal differed from the consumption-side distribution. Xinjiang had the largest production-side total (approximately 268 × 10^8 m^3), followed by Heilongjiang (155 × 10^8 m^3) and Jiangsu (129 × 10^8 m^3). Hunan, Guangdong, and Guangxi each exceeded 100 × 10^8 m^3. At the lower end, Beijing, Tianjin, Shanghai, Qinghai, Chongqing, Hainan, and Tibet each had less than 20 × 10^8 m^3 under the selected household final-demand boundary.

Agricultural-stage value added followed a different provincial ordering. Sichuan had the largest production-side total (approximately 3182 × 10^8 CNY), followed by Henan (3041 × 10^8 CNY), Shandong (2779 × 10^8 CNY), Guangdong (2708 × 10^8 CNY), Jiangsu (2477 × 10^8 CNY), and Hunan (2456 × 10^8 CNY). Xinjiang, despite ranking first in attributed agricultural water withdrawal, generated approximately 1088 × 10^8 CNY of agricultural-stage value added. Heilongjiang ranked second for attributed withdrawal but eleventh for agricultural-stage value added (approximately 1940 × 10^8 CNY).

Production-side withdrawal includes amounts attributable to household demand within the producing province and in other provinces. Of Xinjiang's attributed production-side total, approximately 184 × 10^8 m^3 (68.7%) was associated with selected household

demand in other provinces; the corresponding amount for Heilongjiang was 117 × 10^8 m^3 (75.6%). Figure 3 displays the 30 largest interprovincial producer–consumer links as arrows, while node sizes summarize each province's total interprovincial outflow or inflow.

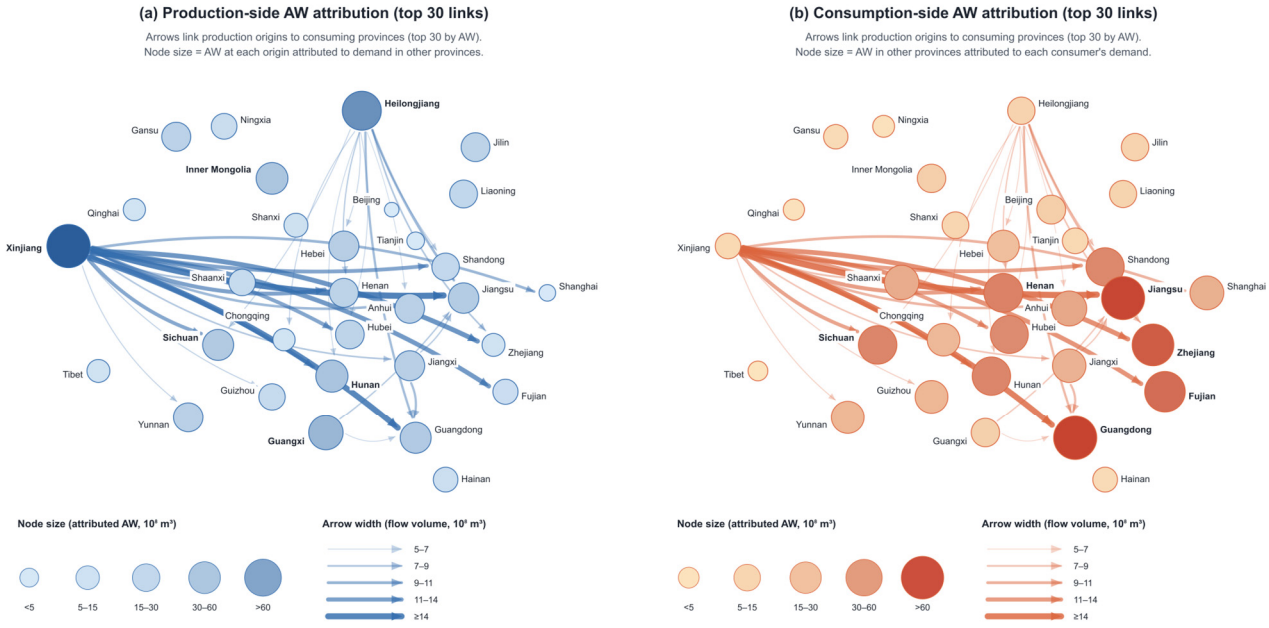

Figure 3. Top 30 interprovincial producer-to-consumer agricultural water-withdrawal attribution links. Panel (**a**) scales nodes by withdrawal at each production origin attributable to demand in other provinces; panel (**b**) scales nodes by withdrawal in other provinces attributable to each consuming province's demand. Node sizes include all interprovincial links, while arrows show the top 30. Arrow width represents attributed withdrawal; the links do not depict physical water transfers.

3.3. Spatial Mismatch Between Agricultural-Stage Value Added and Agricultural Water Withdrawal

Dividing each production-side account by its respective national attributed total showed differences in provincial shares. Thirteen of the 31 provinces had negative share differences ($D_r < 0$), indicating that their national shares of attributed agricultural water withdrawal exceeded their shares of agricultural-stage value added. The remaining 18 provinces had positive differences.

Xinjiang had the largest negative share difference, at −11.55 percentage points. It accounted for 14.07% of national attributed agricultural water withdrawal but 2.52% of agricultural-stage value added. Heilongjiang had the second-largest negative difference (−3.64 percentage points); the other negative differences reported in Table 3 were smaller in magnitude.

Table 3. Producing provinces with the five largest negative and five largest positive agricultural-stage value-added-minus-water share differences.

Province	AW (10^8 m^3)	AW Share (%)	Agricultural-Stage VA (10^8 CNY)	VA Share (%)	D_r (pp)	Aqueduct Class
Xinjiang	268.18	14.07	1088.02	2.52	−11.55	Extremely High
Heilongjiang	155.05	8.14	1940.21	4.50	−3.64	Low–Medium
Jiangxi	79.27	4.16	1098.49	2.55	−1.61	Low–Medium
Inner Mongolia	75.57	3.97	1107.87	2.57	−1.40	Extremely High
Ningxia	32.33	1.70	196.65	0.46	−1.24	High

Table 3. *Cont.*

Province	AW (10^8 m^3)	AW Share (%)	Agricultural-Stage VA (10^8 CNY)	VA Share (%)	D_r (pp)	Aqueduct Class
Henan	66.72	3.50	3041.24	7.05	+3.55	Extremely High
Shandong	64.35	3.38	2778.59	6.44	+3.06	Extremely High
Sichuan	86.91	4.56	3181.91	7.38	+2.82	High
Hebei	58.51	3.07	2241.73	5.20	+2.13	Extremely High
Guizhou	29.65	1.56	1528.08	3.54	+1.99	Low–Medium

Note: D_r = agricultural-stage value-added share minus agricultural water-withdrawal share. Values are selected by D_r solely for compact main-text presentation; all 31 provinces remain in the analysis.

Xinjiang's baseline agricultural-withdrawal coefficient was 1524.38 m^3 per 10,000 CNY of Sector 1 gross output, the highest among the 31 provinces and 7.01 times their median. Its attributed agricultural-stage value added per cubic meter was 4.06 CNY, compared with 22.64 CNY for the national attributed account (Supplementary Material S2, Table S5). These ratios describe the monetary and withdrawal accounts, not physical production efficiency.

The largest positive share differences occurred in Henan (+3.55 percentage points), Shandong (+3.06 percentage points), and Sichuan (+2.82 percentage points). Figure 4 plots the two national production-side shares against the 45° equal-share line, with agricultural-stage value added on the horizontal axis and agricultural water withdrawal on the vertical axis. Provinces above the line have negative D_r, whereas those below it have positive D_r. The main panel enlarges the 0–8% range for 29 provinces; the inset shows all 31 provinces.

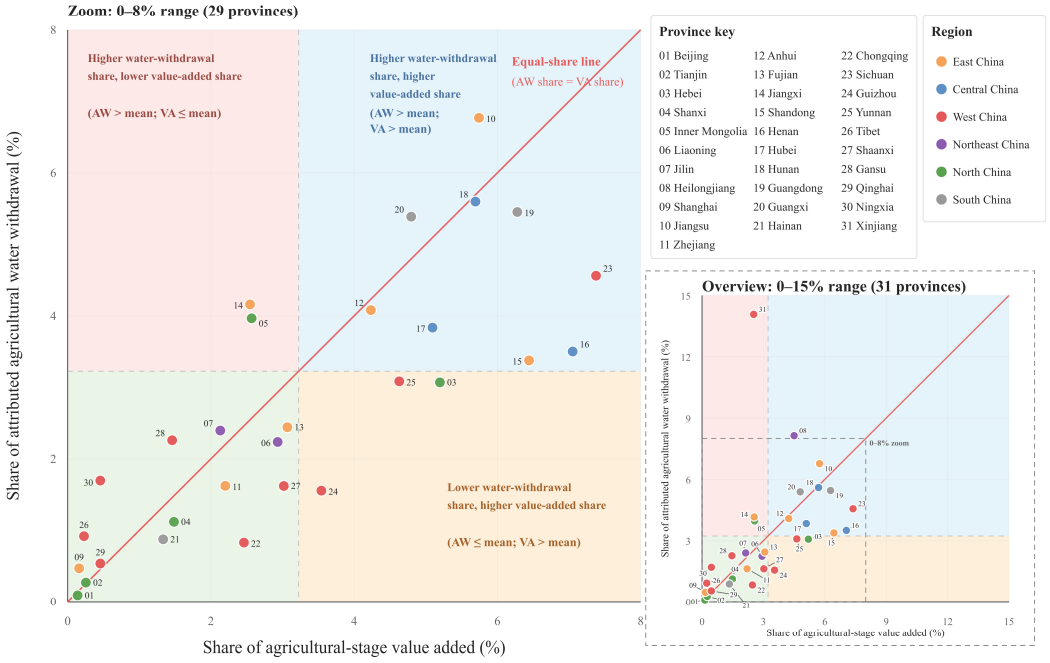

Figure 4. Mismatch between national production-side shares of demand-attributed agricultural water withdrawal and agricultural-stage value added across 31 provinces. The main panel enlarges the 0–8% range for 29 provinces, and the inset retains the full 0–15% range for all provinces. The equal-share line denotes identical national shares; the vertical distance from this line represents the magnitude of the provincial share difference. The dashed horizontal and vertical lines mark the mean provincial share (100%/31 ≈ 3.23%) for each account. The green shaded area indicates provinces whose agricultural water-withdrawal and agricultural-stage value-added shares are both at or below this mean.

Table 3 summarizes the five largest negative and five largest positive share differences. Appendix A (Table A1) reports the corresponding production-side accounts and Aqueduct classes for all 31 provinces.

3.4. Baseline Water-Stress Context of the Spatial Mismatch

Negative share differences occurred both within and outside provinces classified as High or Extremely High baseline water stress. The 13 provinces in these two classes jointly accounted for 40.69% of national attributed agricultural water withdrawal, 38.05% of agricultural-stage value added, and 65.95% of the national negative-mismatch magnitude. Their attributed-withdrawal share exceeded their 40.05% share of the sum of published provincial agricultural withdrawals by only 0.64 percentage points; the latter is a separate production-side composition benchmark. Xinjiang alone accounted for 49.75% of the national negative-mismatch magnitude and 75.43% of that located in the High and Extremely High classes. Only six of the 13 provinces had a negative share difference, so the group aggregate does not represent a uniform pattern across high-stress producers.

The class-level distributions were not monotonic with increasing baseline water stress. Tibet, the only province in the Low class, accounted for 0.9% of attributed agricultural water withdrawal and 0.2% of agricultural-stage value added. Low–Medium stress provinces accounted for 38.6% and 40.0% of these national totals, respectively, while Medium–High provinces accounted for 19.8% and 21.7%. The corresponding shares were 12.3% and 13.9% in the High class and 28.3% and 24.2% in the Extremely High class. Thus, the Extremely High class had a larger water-withdrawal share than agricultural-stage value-added share, whereas the High class showed the reverse at the group level.

Negative share differences also occurred in lower baseline water-stress classes, including Heilongjiang, Jiangxi, Guangxi, Tibet, and Qinghai. Figure 5 shows provincial baseline water-stress scores, class-level shares of attributed agricultural water withdrawal and negative-mismatch magnitude and the cumulative share of negative-mismatch magnitude across provinces ordered by increasing stress.

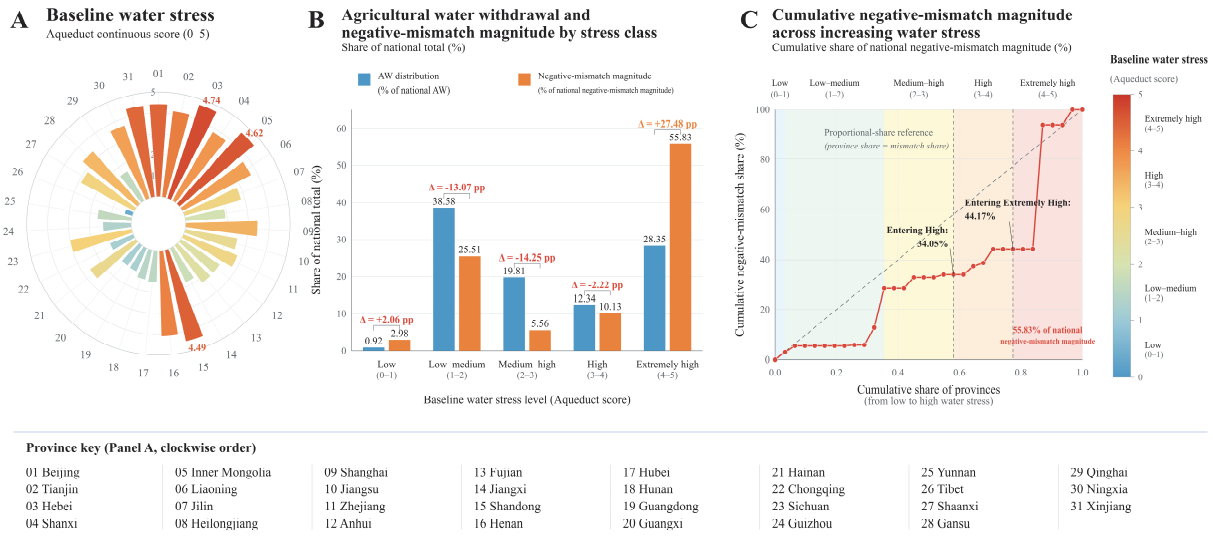

Figure 5. Baseline water stress and the distribution of agricultural water withdrawal (AW) and negative-mismatch magnitude. (**A**) Provincial Aqueduct baseline-water-stress scores, with bar colors corresponding to the color scale. (**B**) Shares of national attributed AW (blue) and negative-mismatch magnitude (orange) by stress class; differences are the latter minus the former, in percentage points. (**C**) Cumulative negative-mismatch share across provinces ordered by increasing water stress (red line). Background colors indicate the five stress classes. The diagonal dashed line represents proportional accumulation, and the vertical dashed lines mark entry into the High and Extremely high classes.

Applying the additional producer–consumer link screen to the 930 directed interprovincial attribution pairs identified 29 links meeting all three conditions. Together, these links accounted for 218.12 × 10^8 m^3, or 21.68% of interprovincial attributed agricultural water withdrawal. Sixteen originated in Xinjiang, nine in Inner Mongolia, and four in Gansu; the ten most negative bilateral share differences all had Xinjiang as the production origin. Removing Xinjiang-origin links from the displayed candidate ranking only, while retaining the original threshold and national denominators, left 13 eligible links from Inner Mongolia and Gansu, representing 47.45 × 10^8 m^3. These bilateral results locate contributions of consuming provinces' selected household demand to producer-side share differences; the screen is descriptive.

3.5. Boundary and Robustness Analyses

Provincial share differences remained similar under the two alternative household final-demand boundaries. Relative to the primary Sector 1 + Sector 6 specification, the Sector 1-only boundary gave a Spearman rank correlation of 0.9976 for D_r, with no provincial sign changes. The Sector 6-only boundary gave a correlation of 0.9952 and changed the sign only in Hunan. The additional link-level screen identified 31 eligible links under Sector 1-only demand and 24 under Sector 6-only demand. The Sector 1-only top-ten candidate set matched the primary set, while the Sector 6-only set shared nine of the primary top ten. Thus, provincial share differences were more stable than the number and ordering of screened bilateral links.

Figure 6 shows the Sector 1 share of attributed agricultural water withdrawal for each cross-provincial producer–consumer pair under the combined demand boundary; the complement is attributable to Sector 6 household demand. This bilateral composition view provides context for the changes in screened-link rankings across the two alternative final-demand boundaries.

Changing the economic-accounting boundary had a larger effect on the share differences. Replacing agricultural-stage value added with full-chain value added, while holding agricultural water withdrawal fixed, reduced the provincial rank correlation to 0.8835. The share difference changed sign in Tianjin, Shanghai, and Anhui, and nine provinces had an absolute change greater than 0.5 percentage points. The comparison shows that some provincial results are sensitive to whether value added is measured at the agricultural stage or across the full domestic production chain.

Alternative water-stress representations did not change D_r, because water-stress information does not enter its calculation. The Aqueduct *bws*/*Tot* and *bws*/*Irr* classifications assigned the same 13 provinces to the combined High and Extremely High group; under either classification, this group accounted for 65.95% of the national negative-mismatch magnitude. Qinghai alone changed class, from Low–Medium to Low, shifting 0.54 percentage points of national attributed withdrawal and 0.35 percentage points of national negative-mismatch magnitude from the former class to the latter; all other class memberships and shares were unchanged. The Spearman correlation between the 2020 annual water-use-to-water-resources ratio and the Aqueduct *bws*/*Tot* score was 0.7802, indicating related but non-equivalent provincial rankings. The correlations of D_r with the Aqueduct score and with the 2020 annual ratio were 0.015 and −0.196, respectively. These weak associations are consistent with the nonmonotonic class-level pattern reported in Section 3.4.

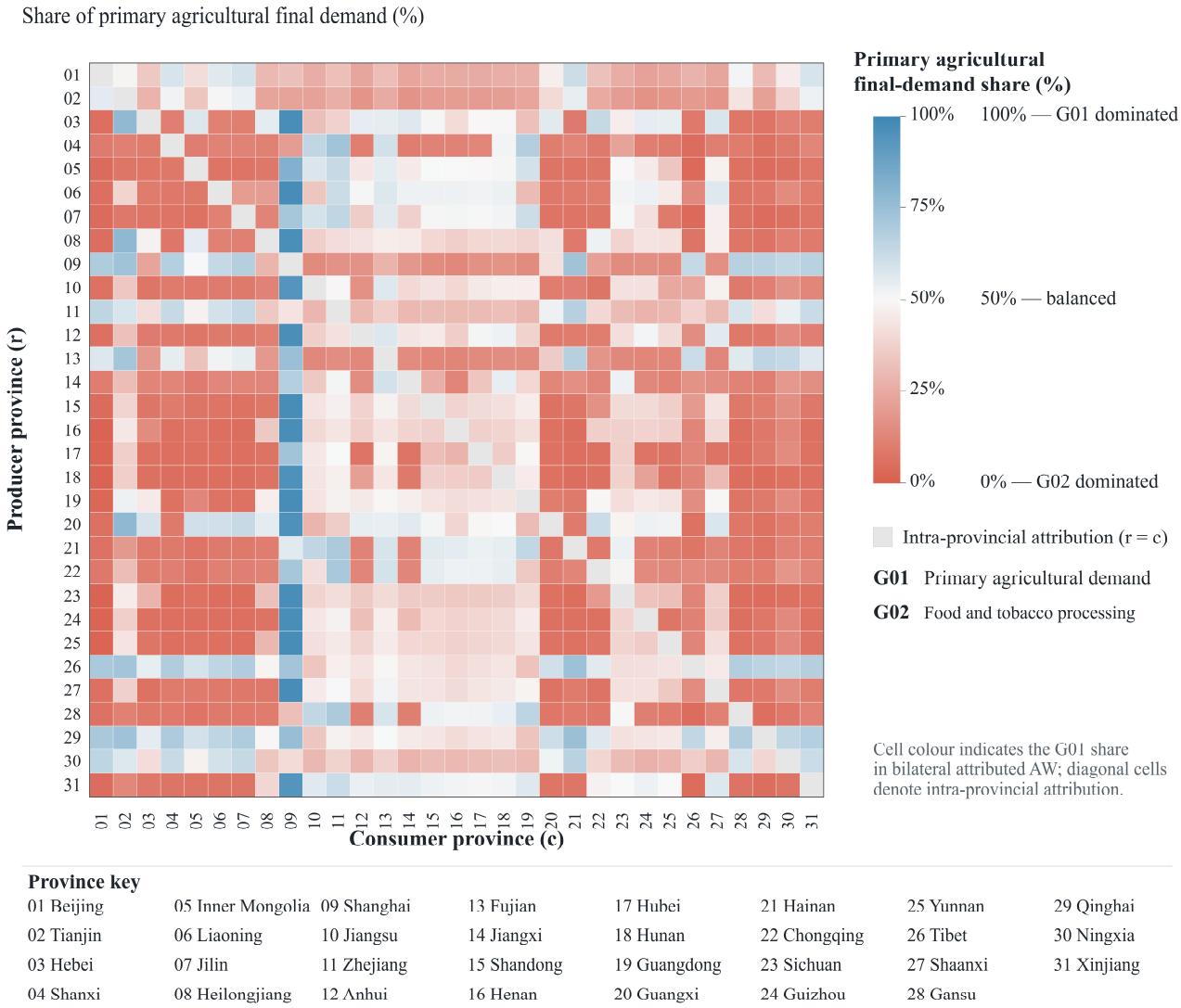

Figure 6. Sectoral composition of bilateral attributed agricultural water withdrawal. Cell color reports the share attributable to Sector 1 household final demand (G01); the complement is attributable to Sector 6 household final demand (G02; Food and Tobacco Processing). Diagonal cells denote intraprovincial attribution, and province numbers follow the embedded key.

The withdrawal-allocation test retained the sign of the share difference in 23 of 31 provinces across all 124 scenarios. Tianjin, Jilin, Jiangsu, Anhui, Hunan, Guangdong, Guangxi, and Qinghai changed sign in at least one scenario; the number of negative differences ranged from 12 to 14, compared with 13 in the baseline. Xinjiang's share difference remained the most negative in every scenario, ranging from −13.90 to −9.06 percentage points. With other provinces' allocations fixed, its effective intensity would need to fall by 84.20% to reach a zero share difference. The High and Extremely High group accounted for 59.80–70.97% of national negative-mismatch magnitude across the scenarios. These conditional ranges show sensitivity to allocation assumptions, not the magnitude of actual aggregation bias (Supplementary Material S1).

Table 4 summarizes the final-demand, economic-accounting, water-stress-context, and withdrawal-allocation checks.

Table 4. Summary of final-demand, economic-accounting, water-stress-context, and withdrawal-allocation checks.

Check	Changed Boundary/Context	Spearman Result	Sign Changes	Key Outcome
Sector 1 only	Final-demand boundary	0.9976	0	31 eligible links; Xinjiang retains the most negative share difference
Sector 6 only	Final-demand boundary	0.9952	1 (Hunan)	24 eligible links; 9 of the top 10 shared with the primary specification
Full-chain VA	Economic-accounting boundary	0.8835	3	Tianjin, Shanghai, and Anhui show sign reversals
Aqueduct bws/Irr	Stress classification	Not applicable	Not applicable	Only Qinghai changes class (Low–Medium to Low); the High + Extremely High share of national negative-mismatch magnitude remains 65.95%
2020 water-use-to-water-resources ratio	Annual stress context	0.7802 with *bws*/*Tot*	Not applicable	Related rankings, but non-equivalent physical boundaries
Withdrawal allocation	Effective intensity of output attributed to selected demand; provincial totals fixed	0.9774–1.0000	8 provinces in at least one of 124 scenarios	Xinjiang remains the most negative; 23 provincial signs remain unchanged (Supplementary Material S1)

Note: Spearman results compare provincial D_r values with the primary specification unless otherwise stated. Sign-change comparisons are not applicable to stress-context checks because water-stress representations do not enter the calculation of D_r.

4. Discussion

4.1. Household Demand Connects Consuming Provinces to Agricultural Water Requirements Beyond Provincial Boundaries

Under the selected household final-demand boundary, 52.81% of attributed agricultural water withdrawal occurred outside the consuming province. Beijing illustrates how this dependence arises in the account: most of its attributed agricultural output was produced elsewhere, and those nonlocal origins had a higher average withdrawal coefficient than local agriculture. Both features contributed to its 90.92% nonlocal withdrawal share. The Leontief calculation includes upstream agricultural inputs into processed products, so this percentage is neither a share of food purchased directly from other provinces nor a physical water-transfer rate. Provincial withdrawal statistics locate extraction; the producer–consumer account identifies the final demand associated with it.

This spatial separation is consistent with studies of provincial water footprints, interprovincial grain trade, and vegetable flows, all of which identify links between demand and water use across regions [4,11,30]. Food-demand and dietary-water studies provide more detail on food categories or scarcity than the present sector-based account [8,10]. Direct comparison of numerical estimates is inappropriate because the studies differ in water indicators, commodities, and accounting boundaries. The present sector-based withdrawal account is therefore distinct from a dietary-water footprint.

The urban–rural comparison indicates that higher selected expenditure per person accounts for the direction of the national per capita withdrawal difference; lower attributed withdrawal per unit of urban expenditure partly offsets it. Differences in the final-demand vectors include the balance between Sectors 1 and 6 and the origins of supply. Because both groups use the same production coefficients, their different expenditure-normalized with-

drawal reflects these demand compositions and associated supply chains. Dietary-water studies also report urban–rural differences [6,7], but the present monetary sector aggregates do not identify specific foods, quantities, or preferences. The calculation therefore supports an expenditure-and-composition explanation within the MRIO account, not a causal claim about urban diets or household income.

4.2. Agricultural Water Withdrawal and Agricultural-Stage Value Added Have Different Provincial Distributions

The production-side accounts have different provincial distributions. Xinjiang illustrates the contrast: it accounted for 14.07% of national attributed agricultural water withdrawal but only 2.52% of agricultural-stage value added, yielding the largest negative share difference (−11.55 percentage points). Heilongjiang also had a negative difference, whereas Henan, Shandong, and Sichuan had positive differences. These comparisons locate differences between two national production-side shares; they are not estimates of provincial water productivity.

Xinjiang's contrast has an accounting explanation. Its large withdrawal coefficient relative to the value-added coefficient gives a lower agricultural-stage value-added-to-withdrawal ratio than the national attributed ratio. With the same induced agricultural output entering both accounts, this makes its water share larger than its value-added share. Demand from other provinces contributes substantially to the scale of that output, as shown in Section 3.2. Under the uniform within-province coefficients, changing the destination of a unit of output does not itself change its water-to-value ratio. This identifies how the model generates the result, but it does not separate the roles of crop mix, irrigation practice, or agricultural prices. Those explanations require disaggregated evidence; the allocation sensitivity test in Section 3.5 addresses only the dependence on the uniform-intensity assumption.

Previous studies have examined water–value differences through interregional transfers, value chains, and scarcity-oriented accounts under varied boundaries [13–18,21,22]. The present analysis addresses a different accounting question: it retains agricultural water withdrawal and agricultural-stage value added as separate accounts, attributes both to the same selected household final demand, and compares their national production-side shares. Matching the production stages is central to this comparison. Agricultural water withdrawal is assigned to Sector 1, and the primary economic account includes value added generated in the same sector. When the economic boundary was expanded to full-chain value added, the share difference changed sign in Tianjin, Shanghai, and Anhui; nine provinces shifted by more than 0.5 percentage points. The broad provincial ranking remained related to the primary result, but these changes show that individual share differences depend on the economic-accounting boundary. Global-value-chain analysis provides another example of how broader production-network accounting changes the scope of virtual-water comparisons [19].

The sign of D_r therefore describes a relationship between two attributed national shares under a specified boundary. It does not establish an income loss, low production efficiency, or inequitable exchange. Such conclusions would require evidence on income and welfare distribution, water-related impacts, and an explicit evaluative benchmark beyond the two accounts compared here.

4.3. Water-Stress Context Qualifies, but Does Not Determine, the Spatial Mismatch

High and Extremely High baseline-water-stress provinces accounted for 65.95% of the national negative-mismatch magnitude, but Xinjiang drove much of this concentration and only six of the 13 provinces in these classes had negative share differences. The aggregate

locates negative mismatches in high-stress origins without implying a uniform or causal stress–mismatch relationship.

High and Extremely High provinces accounted for 40.69% of attributed agricultural water withdrawal, compared with 40.05% of the sum of published provincial agricultural withdrawals. This 0.64-percentage-point difference indicates similar aggregate shares under the selected-demand and official provincial totals.

Negative differences also occurred in lower-stress provinces, including Heilongjiang, Jiangxi, Guangxi, Tibet, and Qinghai. The Spearman correlation between D_r and the Aqueduct *bws*/*Tot* score was 0.015, consistent with no monotonic provincial association in this cross-section. Local or seasonal constraints require finer-scale evidence.

Scarcity-oriented food and trade studies report heterogeneous water pressures across products and production origins [8,9,12,23,31–35]. These measures draw on information beyond the physical withdrawal volumes used here. Aqueduct is retained as long-run production-origin context and does not alter the producer–consumer water or value-added accounts or D_r.

A negative share difference in a High or Extremely High province marks a co-occurrence with long-run stress. Its local implications depend on irrigation, crop mix, and finer-scale water availability; provincial classes alone cannot determine an intervention.

4.4. Implications for Producer–Consumer Coordination and Agricultural Value Creation

Provincial water and agricultural authorities can use the paired accounts to identify production origins and consuming provinces for joint assessment. Where large attributed withdrawals coincide with negative share differences and high baseline stress, a first step is to examine crop-level water use and local hydrological conditions. This information is needed to evaluate irrigation or production measures and their water savings, feasibility, and economic effects. Related food-trade and water–energy–food studies assess trade-related water scarcity and risk using additional analyses [36,37].

Consuming provinces with strong nonlocal dependence, such as Beijing, can use the identified production origins to target requests for information on water conditions in supplying regions. Shifting demand to another province could move rather than reduce water pressure. Global trade studies find that water-saving and scarcity outcomes depend on origin and network pathways [38,39]; any proposed demand intervention in China would need to account for displaced water and economic effects across the interprovincial system.

A large negative share difference may also motivate closer examination of how agricultural-stage value added is generated, including the roles of product quality, producer organization, and market access. The full-chain sensitivity check shows why the economic stage must be specified: downstream processing, transport, and service value added belong to the broader full-chain account.

Earlier virtual-water and value-trade studies have proposed ecological compensation [13,15]. The present accounts locate differences between attributed agricultural water-withdrawal and agricultural-stage value-added shares and identify the consuming provinces contributing to those differences. They do not establish an entitlement to compensation or determine a transfer price. These producer–consumer links do not assign legal responsibility for withdrawal to consuming provinces. A compensation rule would require evidence on hydrological impacts, costs, income distribution, and institutional responsibility. The findings therefore provide a basis for producer–consumer dialogue and further evaluation, rather than a monetary formula.

4.5. Limitations and Future Research

First, the selected household final-demand boundary approximates agri-food-related demand rather than total household food consumption. Sector 1 combines agriculture, forestry, animal husbandry, and fishery, while Sector 6 combines food processing and tobacco; food services cannot be separated reliably from accommodation in the 42-sector MRIO. The Sector 1-only and Sector 6-only checks leave the broad provincial mismatch pattern largely intact, but neither separates activities within those sectors. More detailed production and consumption data would allow food products, tobacco, and food services to be distinguished.

Second, each published provincial agricultural water-withdrawal total is assigned to Sector 1 as an input to the water satellite account. Applying one direct intensity to all Sector 1 output in that province cannot resolve differences among crops and livestock systems, irrigation technologies, or locations within the province. If the agricultural output serving the selected demand is more water-intensive than the provincial average, the baseline underestimates its attributed withdrawal; if it is less water-intensive, the baseline overestimates it. Available accounts do not establish which case applies in each province or the size of the bias. Irrigated-area weights alone cannot identify this allocation without compatible crop or subsector water accounts and production-to-demand mappings. The one-province-at-a-time test examines conditional sensitivity while preserving official totals; it neither reconstructs crop-level allocation nor assesses simultaneous changes across provinces. The attributed account measures withdrawal, not consumptive blue-water use; return flows and local hydrological effects cannot be inferred from it. Aqueduct describes long-run province-level baseline stress rather than conditions at particular withdrawal sites in 2020. More detailed agricultural water accounts could help assess local consequences when combined with basin- or grid-level hydrological information. Relevant information includes consumptive water use, water availability, and environmental-flow requirements.

Third, the economic and water accounts describe 2020 alone, so they cannot establish whether the spatial patterns persist or distinguish year-specific disturbances from longer-term changes. The 2020 annual water-use-to-water-resources ratio and Aqueduct's long-run baseline score also differ in period and hydrological boundary. A multi-year extension is warranted but is not implemented here: it requires MRIO tables with harmonized sector and regional definitions, year-matched agricultural-withdrawal accounts, and consistent population denominators. Monetary comparisons also require attention to price changes. Such an extension could assess changes in demand, production structure, and water intensity; the present analysis neither estimates temporal effects nor projects future patterns.

Fourth, the domestic MRIO records imported intermediate content but does not identify foreign production origins or their agricultural water and value-added intensities. The estimates therefore cover domestic production induced by the selected household demand, not a complete global consumption footprint. Global evidence on the scarcity of imported virtual water [39] and research on food imports and production water pressure in China [40] show why trade beyond the domestic system matters, but neither supplies the missing foreign production accounts for this model. Linking the provincial MRIO to a global MRIO or a commodity-specific trade model would make foreign-source attribution possible.

Finally, the share-difference measure and its bilateral decomposition are descriptive accounting constructs; they do not explain the mechanisms generating the observed spatial pattern. Future work on welfare, equity, or compensation would require evidence on behavioral responses, income distribution, water-related damages, and explicit institutional and normative criteria in addition to the accounts developed here.

5. Conclusions

This study used a provincial multi-regional input–output framework to attribute agricultural water withdrawal and agricultural-stage value added to selected rural and urban household agri-food-related final demand across China's 31 provinces in 2020. Both accounts were traced through domestic production under the same final-demand boundary, with value added measured at the agricultural production stage to maintain stage alignment with the water account. Baseline water stress was examined separately as a characteristic of production origins. The selected Sector 1 + Sector 6 boundary is a sector-based proxy for agri-food-related demand, not a complete measure of household food consumption.

Under this boundary, 1905.49 $\times$ 10^8 m^3 of agricultural water withdrawal and 43,132.38 $\times$ 10^8 CNY of agricultural-stage value added were attributed to selected household demand. Of these totals, 52.81% and 49.28%, respectively, occurred outside the consuming province. The amount attributable to a province's household demand did not necessarily correspond to its reliance on production elsewhere. Production-side and consumption-side accounts therefore reveal different aspects of interprovincial agricultural water dependence.

The two accounts also followed different production geographies. Thirteen provinces had a negative value-added-minus-water share difference, and Xinjiang had the most negative difference, at −11.55 percentage points. High and Extremely High baseline-water-stress provinces accounted for 65.95% of the national negative-mismatch magnitude, but Xinjiang strongly influenced this aggregate, and negative differences also occurred in lower-stress provinces. Baseline stress thus provides long-run water-stress context for the production origin at which a share difference occurs; it neither determines that difference nor measures the local consequences of withdrawal. Xinjiang remained the most negative province under the tested within-province withdrawal allocations, although some provincial signs changed. The provincial pattern changed little when household final demand was restricted to either selected sector. In contrast, replacing agricultural-stage with full-chain value added reversed the sign of the share difference in three provinces, underscoring the importance of specifying the economic production stage.

Provincial water and agricultural authorities can use these accounts to identify production origins and consuming provinces for joint assessment. For Xinjiang and other origins combining large attributed withdrawals, negative share differences, and high baseline stress, crop-level and local hydrological assessments are needed before selecting production measures. For consuming provinces such as Beijing, the accounts identify supplying origins whose water conditions merit closer examination. Any proposed sourcing or production change should be assessed for water and economic effects across affected provinces. A negative share difference alone does not establish production inefficiency, inequitable exchange, or a compensation obligation. Multi-year and finer-scale data are needed to evaluate responses and assess whether the observed patterns persist.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w18212664/s1: Supplementary Material S1 provides the withdrawal-allocation sensitivity method. Table S1. Provincial share differences and own-province zero-crossing thresholds; Table S2. Ranges across the 62 scenarios at each illustrative perturbation level. Supplementary Material S2 provides the urban–rural, Xinjiang, and Beijing accounting calculations. Table S3. National urban–rural accounting comparison; Table S4. Selected expenditure, attributed withdrawal, and their composite intensity by consuming province; Table S5. Xinjiang inputs and corresponding baseline attribution; Table S6. Agricultural production and withdrawal attributed to Beijing's selected household demand by origin.

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Data Availability Statement: The data used in this study are available from publicly accessible sources. The 2020 China provincial multi-regional input–output table is available from Figshare at https://doi.org/10.6084/m9.figshare.29927291 [25]. Provincial agricultural water-withdrawal data are available from the China Water Resources Bulletin 2020 at https://slqjd.mwr.gov.cn/szygb/2022-09-23/332.html (accessed on 25 September 2026) [26], Population data are available from the China Statistical Yearbook 2021 at https://www.stats.gov.cn/sj/ndsj/2021/indexch.htm (accessed on 25 September 2026) [28], and baseline water-stress data are available from WRI Aqueduct 4.0 at https://www.wri.org/data/aqueduct-40-country-rankings (accessed on 25 September 2026) [27]. The withdrawal-allocation sensitivity results and the supporting urban–rural, Xinjiang, and Beijing calculations are provided in Supplementary Materials S1 and S2. The complete baseline production-side provincial results are reported in Appendix A (Table A1).

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Appendix A. Complete Provincial Production-Side Results

Table A1. Baseline agricultural water withdrawal, agricultural-stage value added, and share differences for all 31 producing provinces in 2020.

Province	AW (10^8 m^3)	AW Share (%)	Agricultural-Stage VA (10^8 CNY)	VA Share (%)	Share Difference (pp)	Aqueduct Class
Beijing	1.73	0.09	59.97	0.14	+0.05	Extremely High
Tianjin	5.14	0.27	110.00	0.26	−0.01	Extremely High
Hebei	58.51	3.07	2241.73	5.20	+2.13	Extremely High
Shanxi	21.34	1.12	640.19	1.48	+0.36	High
Inner Mongolia	75.57	3.97	1107.87	2.57	−1.40	Extremely High
Liaoning	42.62	2.24	1264.88	2.93	+0.70	High
Jilin	45.67	2.40	919.26	2.13	−0.27	Medium–High
Heilongjiang	155.05	8.14	1940.21	4.50	−3.64	Low–Medium
Shanghai	8.95	0.47	69.33	0.16	−0.31	High
Jiangsu	128.98	6.77	2476.83	5.74	−1.03	Medium–High
Zhejiang	30.92	1.62	949.41	2.20	+0.58	Medium–High
Anhui	77.75	4.08	1826.19	4.23	+0.15	Medium–High
Fujian	46.55	2.44	1323.16	3.07	+0.62	Medium–High
Jiangxi	79.27	4.16	1098.49	2.55	−1.61	Low–Medium
Shandong	64.35	3.38	2778.59	6.44	+3.06	Extremely High
Henan	66.72	3.50	3041.24	7.05	+3.55	Extremely High

Table A1. *Cont.*

Province	AW (10^8 m^3)	AW Share (%)	Agricultural-Stage VA (10^8 CNY)	VA Share (%)	Share Difference (pp)	Aqueduct Class
Hubei	73.09	3.84	2197.24	5.09	+1.26	Low–Medium
Hunan	106.67	5.60	2455.80	5.69	+0.10	Low–Medium
Guangdong	103.90	5.45	2707.92	6.28	+0.83	Low–Medium
Guangxi	102.64	5.39	2068.82	4.80	−0.59	Low–Medium
Hainan	16.69	0.88	575.40	1.33	+0.46	Medium–High
Chongqing	15.81	0.83	1061.66	2.46	+1.63	Low–Medium
Sichuan	86.91	4.56	3181.91	7.38	+2.82	High
Guizhou	29.65	1.56	1528.08	3.54	+1.99	Low–Medium
Yunnan	58.78	3.08	1996.92	4.63	+1.55	Low–Medium
Tibet	17.52	0.92	98.52	0.23	−0.69	Low
Shaanxi	30.90	1.62	1301.78	3.02	+1.40	Medium–High
Gansu	43.08	2.26	629.37	1.46	−0.80	High
Qinghai	10.23	0.54	196.94	0.46	−0.08	Low–Medium
Ningxia	32.33	1.70	196.65	0.46	−1.24	High
Xinjiang	268.18	14.07	1088.02	2.52	−11.55	Extremely High
National total	**1905.49**	**100.00**	**43, 132.38**	**100.00**	**0.00**	**—**

Note: AW denotes agricultural water withdrawal; VA denotes agricultural-stage value added. Both are production-side amounts attributed to the selected household final demand for Sectors 1 and 6, not total provincial agriculture. Each share uses its own national attributed total. The share difference is the VA share minus the AW share, in percentage points (pp), calculated before rounding. Aqueduct classes use the baseline *bws*/*Tot* classification. Displayed values may not sum exactly because of rounding; provinces follow the MRIO order. The national total row is shown in bold to distinguish national aggregate values from provincial results.

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