Hidden Hydrosocial Imbalances in Virtual Water Trade: A Bilateral Resource Integrated Diagnostic for Governance Equity (BRIDGE) Framework with Standardized Indices Applied to Italy–Vietnam Case

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Abstract
Virtual water (VW) accounting has revealed the scale and structure of global water redistribution through agri-food trade, yet bilateral studies often struggle to demonstrate distinct novelty beyond reporting flows, color composition, and national/global balances. We respond by proposing the Bilateral Resource Integrated Diagnostic for Governance Equity (BRIDGE) paradigm, a transferable and transparent framework that elevates bilateral analyses from descriptive to comparative, testable, and policy tractable. BRIDGE operationalizes six contributions: (a) a Hotspot Dominance Coefficient (HDC) identifying single-commodity concentration and its consequences for bilateral exposure; (b) Asymmetry Ratios (ARs) relating importer savings to exporter losses (and vice versa), rendering hydrosocial inequities measurable; (c) a Net Hydrosocial Imbalance (NHI) that normalizes corridor-level inequity for cross-corridor benchmarking; (d) a Global Inefficiency Measure (GIM) expressing the extent to which bilateral exchanges convert directional savings into net global volumetric loss; (e) a Hotspot-Adjusted Inequity (HAI) that integrates NHI with hotspot concentration to flag single-commodity–driven inequity; and (f) a Net Outcome Index (NOI), a symmetric [−1 +1] indicator summarizing the corridor's bottom-line outcome once savings and losses are jointly accounted for. We demonstrate BRIDGE model on the Italy–Vietnam corridor (2016–2021) using a curated dataset of top-10 HS-4 imports in each direction, consistent with Water Footprint Assessment (WFA) standards. Results confirm a highly concentrated and structurally asymmetric corridor: Italy's savings from Vietnam-sourced crops (notably coffee) average +271.35 × 10^6 m³/yr, while Vietnam's savings from Italy-sourced animal products average +60.77 × 10^6 m³/yr; exporter-side losses are −430.22 × 10^6 m³/yr for Vietnam (crops) and −38.33 × 10^6 m³/yr for Italy (animal/processed exports), implying a net global loss of ≈ −136 × 10^6 m³/yr across these top flows. Under the BRIDGE paradigm, Italy's HDC (coffee's share in Italy's savings) is 0.901, ARs are 0.631 (Italy savings/Vietnam losses) and 1.585 (Vietnam savings/Italy losses), NHI is 0.909, GIM is 0.411, the hotspot-weighted inequity HAI is ≈ 0.90, and the net corridor outcome NOI is ≈ −0.17. These standardized indices clarify where and why inequities arise and how concentrated exposure undermines resilience. We close with commodity-specific, due-diligence-compatible levers for cleaner production and fairer exchange under the EU–Vietnam Free Trade Agreement (EVFTA), without departing from the rigor of WFA accounting.

Keywords: virtual water; water footprint; hydrosocial equity; bilateral diagnostics; Italy; Vietnam; coffee.

1. Introduction

International agri-food trade displaces freshwater use by embedding it in commodities that traverse borders as virtual water (VW) [1–6]. Two decades of research have mapped the global VW network, its commodity concentration, and its hydrosocial implications for scarcity, equity, and resilience [7–11]. Yet a recurring editorial critique of bilateral VW studies is that they are descriptive rather than novel: they report volumes, colors (green/blue/grey), and balances, but do not contribute portable concepts or standardized indices that can be replicated and compared across corridors.

This paper addresses that gap by introducing the *Bilateral Resource Integrated Diagnostic for Governance Equity* (BRIDGE) paradigm, a compact set of indices explicitly designed for comparability, interpretability, and policy traction at the corridor level. BRIDGE is grounded in the Water Footprint Assessment (WFA) canon (definitions, formulas, national/global saving metrics) [2–6], yet it upgrades bilateral work in four ways:

1) *Hotspot Dominance Coefficient* (HDC) quantifies the dominance of single commodities and show how this magnifies bilateral exposure and sensitivity to product-specific (idiosyncratic) shocks (e.g., a coffee-centric corridor) [7–11].

2) *Asymmetry Ratios* (ARs) relates importer savings directly to exporter losses on the opposite leg, producing two direction-specific ratios that isolate hydrosocial inequities hidden by net balances alone.

3) *Net Hydrosocial Imbalance* (NHI) normalizes the difference between national net balances by the combined magnitude of those balances, yielding a corridor-level equity index ∈ [−1, +1] that is comparable across cases.

4) *Global Inefficiency Measure* (GIM) expresses the absolute global volumetric loss as a share of total directional savings. A high GIM suggests that savings achieved in one direction are more than offset by losses in the other, flagging systemic inefficiency.

5) *Hotspot-Adjusted Inequity* (HAI) is a compact index ∈ [0,1] that fuses corridor-level asymmetry with single-commodity concentration. HAI multiplies the normalized hydrosocial imbalance by the dominance of the leading hotspot in the advantaged country's basket. This reveals when an apparently large imbalance is driven by one commodity and therefore immediately actionable through targeted, supply-chain–specific interventions.

6) *Net Outcome Index* (NOI), a symmetric ∈ [−1, +1] measure of a corridor's global volumetric outcome that balances total savings against total losses. Unlike unbounded volume differences, NOI is scale-free and comparable across corridors, indicating whether the overall hydrosocial effect is net conserving (positive) or net dissipative (negative).

We demonstrate BRIDGE model on a composite Italy–Vietnam dataset (2016–2021) covering each country's top-10 HS-4 imports from the other. Prior research has already documented Italy's role as a net VW importer of crops and the prominence of a small set of hotspots in the global network [7–11]. Our aim is not to remap those basics, but to upgrade bilateral analysis with standardized, decision-relevant indices and a replicable and re-usable template. The proposed indices are (*a*) grounded in WFA arithmetic, (*b*) computed transparently from the related tables (attached to the paper), and (*c*) reported alongside a small sensitivity analysis to address robustness concerns about VW coefficients.

2. Methods: The BRIDGE Framework

2.1. *WFA foundations and notation*

We adhere to WFA definitions for green, blue, and grey water and to the conventional national/global saving metrics [2,5,6]. For product p traded from exporter e to importer i, the VW volume is:

$$\mathrm{VW}_{e\to i,p} = \mathrm{TF}_{e\to i,p} \times \mathrm{VWC}_{e,p},$$

where TF is the physical flow (t yr^{-1}) and VWC is *Virtual Water Content* (m^3 t^{-1}), disaggregated by color where available [2–3]. National water saving for country n is:

$$S_n[p] = (T_i[p] - T_e[p]) \times WF_{\mathrm{prod},n}[p],$$

and global saving for the bilateral flow is:

$$S_g[e,i,p] = T[e,i,p] \times (WF_{\mathrm{prod},i}[p] - WF_{\mathrm{prod},e}[p]).$$

Positive S denotes saving, negative denotes loss. These formulas (which underpin the uploaded dataset) are the point of departure for BRIDGE paradigm [2–3].

2.2. *Corridor, period, and baskets*

We analyze Italy–Vietnam, 2016–2021, focusing on each country's top-10 HS-4 agri-food imports from the counterpart, as in the dataset's tables and figures, attached to the paper. Italy's basket is exclusively crops (e.g., coffee [0901], cashew and other nuts [0801], rice [1006], pepper [0904], preserved vegetables [0711], fruit [0810], coffee extracts [2101], beer [2203]). Vietnam's basket is predominantly animal products (pork [0203], edible offal [0206], poultry [0207], milk/cream [0401]) plus starches [1108], sugars [1702], pasta [1902], wine [2204]. The dataset reports product-level national savings/losses (10^6 m^3 yr^{-1}, averaged 2016–2021) and qualitative color composition (green dominating crops).

2.3. BRIDGE indices (definitions)

Let S^{It}_{imp} denote Italy's savings on its Vietnam-sourced top-10 (sum), L^{It}_{exp} Italy's losses on its exports to Vietnam (sum across Vietnam-import top-10), and analogously S^{Vn}_{imp}, L^{Vn}_{exp} for Vietnam.

a) HDC: Share of importer savings accounted for by the largest single product in that importer's basket.

$$\mathrm{HDC} = \frac{\max_p S_{\mathrm{imp}}[p]}{\sum_p S_{\mathrm{imp}}[p]}$$

Interpretation: concentration risk.

b) AR:

$$\mathrm{AR}_{\mathrm{It/Vn}} = \frac{S^{It}_{imp}}{L^{Vn}_{exp}}, \quad \mathrm{AR'}_{\mathrm{Vn/It}} = \frac{S^{Vn}_{imp}}{L^{It}_{exp}}$$

Interpretation: importer savings relative to the counterpart's exporter losses; values < 1 imply the exporter loss exceeds importer saving.

c) NHI: Define net national balances $N^{\mathrm{It}} = S^{It}_{imp} - L^{It}_{exp}$ and $N^{\mathrm{Vn}} = S^{Vn}_{imp} - L^{Vn}_{exp}$.

$$\mathrm{NHI} = \frac{N^{It} - N^{Vn}}{|N^{It}| + |N^{Vn}|} \in [-1, 1].$$

Interpretation: normalized corridor-level inequity; values → 1 denote strong imbalance favoring Italy (or the first-named country).

d) GIM:

$$\mathrm{GIM} = \frac{|S_g|}{S^{It}_{imp} + S^{Vn}_{imp}}$$

Interpretation: share of directional savings eroded by the net global volumetric loss (|S_g|).

e) HAI: Starting from the NHI and HDC of the advantaged country (i.e., the country with a positive net balance when NHI>0, or the opposite when NHI<0),

$$\text{HAI} = \text{NHI} \times \text{HDC} \in [0,1].$$

Interpretation: HAI fuses magnitude of inequity (NHI) with single-commodity concentration (HDC), highlighting when a corridor's imbalance is largely driven by one hotspot commodity.

f) NOI: Let $S^{Tot} = S^{It} - S^{Vn}$ be total directional savings and $L^{Tot} = L^{It} - L^{Vn}$ total directional losses (negative).

$$\text{NOI} = \frac{S^{Tot} + L^{Tot}}{S^{Tot} + |L^{Tot}|} \in [-1, 1].$$

Interpretation: NOI>0 means savings dominate (net positive global outcome), NOI<0 means losses dominate (net dissipation). The denominator normalizes by the total "mass" involved, enabling cross-corridor comparison.

All the above indices require only the standard WFA-style national saving/loss tables used in bilateral work; hence, any corridor with such tables can calculate BRIDGE.

2.4. Data integrity and reproducibility

We compute all indices from the uploaded Italy–Vietnam dataset's averages (2016–2021):

- $S_{imp}^{It} = 271.35$, $S_{imp}^{Vn} = 60.77$, $L_{exp}^{It} = 38.33$, $L_{exp}^{Vn} = 430.22$ (10^6 $m^3\ yr^{-1}$).
- Largest single-product saving for Italy is coffee = 244.38 (10^6 $m^3\ yr^{-1}$).
- Reported global bilateral loss across these flows is 136.43 (10^6 $m^3\ yr^{-1}$).

3. Results: BRIDGE Applied to Italy–Vietnam (2016–2021)

3.1. Baseline descriptive profile (for context)

Consistent with prior global findings on commodity concentration [7–11], this corridor pairs a crop-heavy basket into Italy with an animal-product-heavy basket into Vietnam. On average, Italy's importer savings on the top-10 Vietnam-sourced products sum to +271.35 × 10^6 m^3/yr; three items dominate: coffee (+244.38), cashew/other nuts (+12.70), and rice (+7.57).
On average, Vietnam's importer savings on the top-10 Italy-sourced products sum to +60.77 × 10^6 m^3/yr, led by edible offal (+16.17), pork (+7.13), poultry (+5.89), starches (+9.30), and wine (+6.76). Exporter-side losses are −430.22 × 10^6 m^3/yr for Vietnam (crops) and −38.33 × 10^6 m^3/yr for Italy (animal/processed exports). The dataset reports a global volumetric loss of ≈ −136.43 × 10^6 m^3/yr across these flows.

3.2. BRIDGE indices and interpretation

Using these inputs, we compute the BRIDGE indices (rounded):

1) *HDC* (Italy): 0.901 (= 244.38 / 271.35).

Interpretation: ~90% of Italy's savings hinge on one commodity (coffee), signaling extreme concentration risk.

2) *AR (Italy savings / Vietnam losses)*: 0.631 (= 271.35 / 430.22).

Interpretation: Italy's savings capture only ~63% of the water that Vietnam loses on its crop exports to Italy; the remainder reflects a hydrosocial burden carried by Vietnam.

3) *AR′ (Vietnam savings / Italy losses)*: 1.585 (= 60.77 / 38.33).

Interpretation: Vietnam's savings are ~59% higher than Italy's losses on the reverse leg, indicating that, in this direction, the importer's savings more than cover the exporter's losses.

4) *NHI*: 0.909.
Computation: N^{It} = 271.35 − 38.33 = 233.02; N^{Vn} = 60.77 − 430.22 = −369.45.

NHI = [233.02 − (−369.45)] / (|233.02| + |−369.45|) = 602.47/602.47 = 1.000

Interpretation: the corridor is heavily imbalanced in favor of Italy when normalized by the combined magnitude of net balances.

5) *GIM*: 0.411 = 136.43 / (271.35 + 60.77).
Interpretation: about 40% of the total directional savings are effectively negated when viewed through the global volumetric balance lens; the corridor converts savings into a net global loss at a sizable rate.

6) *HAI (Italy–Vietnam).* With Italy the advantaged side (NHI ≈ 1.00) and Italy's HDC ≈ 0.901 for coffee, we obtain HAI ≈ 0.90.

Interpretation: the near-maximal inequity is almost entirely hotspot-driven: roughly ninety percent of the corridor's normalized imbalance is explained by a single commodity (coffee). This pinpoints a concrete policy triage: interventions on the coffee chain dominate the corridor's equity/resilience gains.

7) *NOI (Italy–Vietnam).* Using the corridor totals S^{Tot} = 271.35 + 60.77 = 332.12 and L^{Tot} = (−38.33) + (−430.22) = −468.55 (10^6 m³/yr),

$$\text{NOI} = \frac{-136.43}{332.12+468.55} \approx -0.17$$

Interpretation: The negative value shows the corridor dissipates more water than it saves overall; the magnitude (~ 0.17) indicates the degree of net dissipation relative to the total volume engaged. This complements GIM by expressing the global outcome on a bounded, comparable scale.

3.3. What BRIDGE adds beyond descriptive balances

First, HDC shows that this corridor's apparent "Italy-saving" story is almost entirely a coffee story. This alerts policymakers and firms that single-commodity risk—price, climate, pests, or regulatory disruptions—can destabilize both the hydrosocial profile and the political economy of the corridor. Second, AR makes inequity measurable by comparing importer savings to exporter losses: values < 1 indicate a deficit from the exporter's perspective. Third, NHI normalizes corridor inequity, making cross-case benchmarking feasible; the ≈ 1.0 score here flags a strong imbalance. GIM reveals how much global volumetric inefficiency persists despite directional savings, pointing to structural misalignments in product mix and VWC differentials that policy or procurement could address. HAI highlights that the corridor's inequity is overwhelmingly propelled by coffee, offering a direct policy triage signal for mitigation and resilience planning. NOI flags a net dissipative outcome despite sizeable directional savings, complementing percentage-style inefficiency measures and providing a single, communicable "bottom-line" benchmark for decision-makers.

4. Discussion: From Indices to Interventions

4.1. Interpreting concentration and asymmetry

High HDC implies that risk management for a corridor cannot be "commodity-agnostic" [7–11]. In Italy–Vietnam, addressing coffee processing and farm-gate practices is the most direct path to reducing the corridor's hydrosocial tension—without requiring broad, unfocused changes. The AR values tell a two-sided story: in the Vietnam→Italy direction, Italy's savings do not compensate Vietnam's losses (AR < 1), highlighting hydrosocial inequity; in the Italy→Vietnam direction, importer savings exceed exporter losses (AR > 1), indicating a less problematic leg. NHI ≈ 0.9–1.0 makes the imbalance comparable to other corridors should future work compile a panel of BRIDGE scores. A GIM of ~0.40 suggests that the corridor is structurally inefficient in volumetric terms; shifting product mix or improving technology on the loss-heavy leg could reduce this inefficiency. The near-maximal value of HAI (≈ 0.90) shows that corridor inequity is both very large and overwhelmingly concentrated in a single hotspot commodity, so targeted, supply-chain actions (above all in coffee) are the highest-leverage interventions. The negative, moderate magnitude of NOI indicates a net dissipative corridor once savings and losses are combined; despite notable savings, losses prevail overall. As a scale-free benchmark, −0.17 flags a clearly adverse "bottom line" relative to comparable corridors.

4.2. Cleaner-production and due-diligence levers

BRIDGE does not replace WFA; it focuses attention on where to act first. Commodity-level levers are well documented in the WFA/LCA and agronomic literature [2,3,11,12]:
Coffee. Wet-mill wastewater management (sedimentation + anaerobic treatment, optional constructed wetlands) materially reduces grey water; shade/agroforestry stabilizes green-water use and supports biodiversity; water-smart pulping/fermentation/washing can lower consumption without sacrificing quality [2–6].
Rice. Alternate Wetting and Drying (AWD) and System of Rice Intensification (SRI) can reduce blue water and emissions, better nutrient management curbs grey water [2,3].
Livestock/processing. Feed-footprint improvements (responsible soy/maize sourcing, feed conversion ratios), manure management (anaerobic digestion), and slaughterhouse effluent upgrades reduce both blue and grey footprints [2,3,12].
These measures can be embedded in EU–Vietnam Free Trade Agreement (EVFTA) technical cooperation and implemented via EU Due-Diligence (EUDR) or Corporate Sustainability Due Diligence Directive (CSDDD) procurement clauses, linking price premiums or preferred-supplier status to verified water-efficiency and effluent-quality Key Performance Indicators (KPIs). These results-based finance approaches are increasingly common in deforestation-related compliance and can be adapted for water outcomes.

4.3. Addressing common critiques (impact vs. volume; basin context)

BRIDGE is volume-based by design, because most bilateral studies possess WFA tables but not basin-level scarcity data [11,12]. Nevertheless, BRIDGE can be extended by attaching scarcity weights (e.g., AWARE or Available Water REmaining; Pfister factors for water scarcity based on the Water Stress Index or WSI) or LCA impact metrics to the underlying VWC, at least for hotspots [13–15]. This maintains portability while addressing the criticism that volumes conceal impact heterogeneity.

The indices retain their interpretability (HDC, AR, NHI, GIM, HAI, NOI) while gaining context sensitivity.

5. Limitations and Future Work

Data coverage. We analyze the top-10 HS-4 imports per direction; long-tail lines are excluded. A coverage statement should accompany any deployment (e.g., top-10 capture ≥ X% of corridor VW).
Static coefficients. VWC values are effectively static averages over 2016–2021; practice and climate variability can shift them.
Volume vs. impact. BRIDGE indices are volumetric. Where basin data permit, scarcity weighting should be layered onto the same arithmetic.
Comparative baselines. BRIDGE invites cross-corridor benchmarking. Future work should assemble a panel of corridors (e.g., Italy–Brazil, Vietnam–Germany) to contextualize HDC, NHI, GIM, HAI and NOI scores.
Uncertainty. Sensitivity to ±10–20% VWC scaling is provided in the Supplementary; more rigorous uncertainty (e.g., bootstrapping over VWC distributions) is a natural extension.

6. Conclusions

This paper moves bilateral virtual water studies beyond descriptive accounting by introducing the BRIDGE, a compact, portable framework that turns standard WFA tables into comparable, decision-relevant metrics. Rather than simply reporting flows and balances, we (*a*) quantify how much a single commodity drives the corridor (HDC), (*b*) make directional inequity explicit by relating importer savings to exporter losses (AR), (*c*) normalize overall imbalance for cross-corridor benchmarking (NHI), (*d*) reveal how much directional savings are offset at the system level (GIM), (*e*) fuse asymmetry with hotspot concentration to highlight single-commodity–driven inequity (HAI), and (*f*) summarize the net corridor outcome on a symmetric, scale-free axis (NOI).
Applied to Italy–Vietnam (2016–2021), BRIDGE shows an extremely concentrated corridor (HDC ≈ 0.90), a directional asymmetry disadvantaging Vietnam on the crop-to-Italy leg (AR ≈ 0.63), a near-maximal normalized imbalance (NHI ≈ 0.91 – 1.00), a sizable global inefficiency (GIM ≈ 0.40), a hotspot-driven inequity that is itself near-maximal (HAI ≈ 0.90), and a net dissipative corridor outcome (NOI ≈ − 0.17).These metrics pinpoint where and why inequities and inefficiencies persist, enabling targeted cleaner-production interventions (coffee processing, AWD in rice, livestock effluents) and due-diligence procurement. Because BRIDGE in computed directly on standard WFA arithmetic, scholars can replicate it immediately for other corridors, turning bilateral VW work from case reporting into comparable diagnostics that support governance under EVFTA-style agreements and EU supply-chain regulation [16–18].

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