

Virtual Water in Global Supply Chains: Trade Structure, Industrial Composition, and Policy Levers

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Abstract

Ecological economists and environmental managers increasingly rely on footprint and input–output tools to track how production and trade redistribute pressure on freshwater systems. We provide global evidence on how international supply chains transmit virtual water and how these flows relate to countries’ development paths and structural change. Using the Eora multiregion input–output framework, we construct a matrix of embodied-water flows for 189 countries, 2010–2021, and aggregate it to country-year net virtual water (NVW) positions consistent with national accounts. A simple open-economy mechanism links NVW to trade structure, manufacturing dependence, income and freshwater endowments, generating testable predictions: NVW outflows rise with export intensity and fall with import intensity; reliance on imported manufacturing intermediates is associated with NVW inflows; and renewable freshwater endowments may not predict net-export status when water constraints are slack. Merging the MRIO data with macro indicators, we find strong support for these predictions: exports are positively associated with NVW outflows, imports with inflows, higher manufacturing shares and income with larger NVW inflows, and freshwater endowments lose explanatory power once trade and industrial structure are controlled for. In growth regressions, NVW positions are essentially unrelated to short-run GDP growth, while renewable freshwater endowments are mildly pro-growth, suggesting the absence of a “water resource curse”. The results highlight actionable levers—efficiency improvements, input substitution, diversified sourcing and better disclosure—that can support expansion of water-intensive green manufacturing without systematically undermining development, and offer ecological economics a transparent framework for assessing embodied-water risks in global supply chains.

Keywords: Virtual water; Global supply chains; Multi-region input–output (MRIO); Ecological economics; Trade and industrial structure; Water scarcity and resilience

JEL classification: Q25; Q56; F18; C67; O47

1. Introduction

For ecological economists and environmental managers, a central challenge is to understand how production and trade reallocate pressure on finite freshwater systems, and how these reallocations interact with development paths and structural change. Global supply chains allow water-intensive stages of production to be located far from final consumers, potentially easing local scarcity in some basins while exacerbating it in others. Yet policy and management decisions—from industrial siting and trade agreements to procurement and disclosure—are still often based on territorial indicators of water use rather than on the full chain of embodied-water flows.

The virtual-water and water-footprint literatures have shown that large volumes of freshwater are embodied in traded goods and services and that this “hidden” trade is highly uneven across countries and sectors (Allan 1998; Hoekstra and Hung 2002; Hoekstra and Mekonnen 2012; Mekonnen and Hoekstra 2011; Lenzen, Moran, Bhaduri, Kanemoto, Bekchanov, Geschke, and Ward 2013). Input–output and multi-region input–output (MRIO) models make it possible to follow these flows along complex value chains and to link them to consumption, production, and trade structures (Leontief 1970; Lenzen, Moran, Kanemoto, et al. 2013; Z. Chen et al. 2018; He et al. 2020). At the same time, macroeconomic debates on the “natural resource curse” ask whether resource abundance systematically hampers economic growth and diversification, highlighting channels such as the Dutch disease, volatility, and rent-seeking (Sachs and Warner 1995; Corden 1984; Ploeg 2011; Badeeb, Lean, and Clark 2017). Most of this work, however, focuses on fossil fuels and minerals; water typically appears only in project-level or basin-scale case studies (Hancock and Sovacool 2018; L. Wang et al. 2020).

Many low-carbon technologies use little water in operation, but upstream stages of green infrastructure—from ultrapure-water requirements in photovoltaic manufacturing to the cement and steel embodied in wind turbines and transmission systems—are water intensive and can alter hydrological balances (L. Wang et al. 2020; Demissie, Yan, and Wu 2017; Farina and Anctil 2022). As economies pursue green industrial strategies, water-abundant countries may specialise in exporting large volumes of virtual water embodied in intermediate and capital goods. Whether such specialisation creates a macro-level analogue of the resource curse, or alternatively supports sustainable development, is an open empirical question with direct relevance for ecological economics and the management of supply-chain risk and resilience.

Most virtual-water studies quantify bilateral flows or footprint indicators—often for specific regions, sectors, or consumption bundles—but seldom connect those flows to macro outcomes such as structural change and economic growth, or ask systematically whether renewable freshwater endowments and persistent net virtual-water *export* positions predict different development paths. We address this gap by combining a multi-

region input–*occupancy*–output framework with macroeconomic analysis for 189 countries over the 2010-21 period. Using the Eora MRIO’s harmonised accounts and environmental satellite for water, we construct a bilaterally consistent global matrix of embodied-water flows and aggregate this measure to country-year net positions that are consistent with national accounts. This measurement reveals which economies externalise or import water use through trade and where policy should target efficiency improvements and exposure reduction.

Our contribution is threefold. *First (measurement/data)*, we build a global matrix of virtual-water flows for 189 countries, using an input–*occupancy*–output approach on the Eora MRIO, and translate this data into country-year net-virtual-water (NVW) outflows (and inflows) suitable for econometric analysis. *Second (analytical framework)*, we develop a parsimonious open-economy mechanism linking NVW positions to trade structure (exports and imports), industrial composition (manufacturing and imported intermediates), income, and water endowments. The framework nests standard MRIO accounting, generates signed predictions for how trade and structure shape NVW, and connects directly to policy levers. *Third (empirics)*, we estimate regressions of NVW outflows on these determinants and relate economic growth to water endowments and net flows conditional on economic structure. This approach provides a macro test of our mechanism, yields new information about the redistribution of water use through trade, and speaks to the possibility (or absence) of a “water resource curse” in aggregate data.

Previewing the results, exports are positively associated with net virtual-water outflows and imports with inflows; higher manufacturing shares and higher GDP per capita are linked to larger net inflows, consistent with reliance on imported intermediates. Renewable freshwater endowments are not a robust predictor of net outflows once trade structure and industrial composition are controlled. In economic growth regressions, net virtual-water flows are not related to short-run growth, while renewable freshwater endowments and GDP per capita are positively associated with economic growth. For ecological economics and environmental management, the message is practical: trade structure and industrial composition—*not* water endowments per se—appear to govern countries’ embodied-water balances and development prospects. This finding shifts attention from fixed endowments to manageable levers—production efficiency, input substitution, sourcing diversification, and disclosure—that can align green industrialisation with water-system resilience.

2. Literature review

2.1 Global water footprint

The use of water resources can be divided into agricultural, industrial, residential, and other categories. Residential and other water uses can be considered as direct

consumption, while agricultural and industrial water usage condenses water resources into downstream agricultural products or industrial products. Based on this understanding of water consumption in the production process, (Allan 1998) introduced the concept of virtual water, which refers to the amount of water required in the production of goods and services or the virtual amount of water embedded in goods and services. This concept was first used to calculate the amount of water consumed in the production and distribution of food and consumer goods. Building on this accounting approach, (Hoekstra and Hung 2002) proposed the concept of a water footprint, expanding the perspective of water resource research from production to consumption and examining water consumption throughout the entire life cycle. Subsequent global syntheses quantified magnitudes and geography: (Hoekstra and Mekonnen 2012) provided headline estimates for humanity's water footprint and its distribution, while (Mekonnen and Hoekstra 2011, 2012) decomposed blue/green/grey components and sectoral sources.

Studying the transfer and use of water resources based on the virtual water concept naturally involves input-output methods. Water resources, as production-relevant factors, are an appropriate subject for input-*occupancy*-output techniques (Leontief 1970; Z. Chen et al. 2018; He et al. 2020; Lenzen, Moran, Bhaduri, Kanemoto, Bekchanov, Geschke, and Foran 2013; Mubako, Lahiri, and Lant 2013). The input-output model can be deployed to visualize and evaluate virtual water flow relationships among and within economic sectors, and can be applied to the water footprint measurement of all commodities, including agricultural, service, and industrial products. In particular, multi-region input-output (MRIO) databases allow consistent, country-by-country tracking of embodied water across complex value chains; the Eora MRIO has been foundational for such global studies (Lenzen, Moran, Kanemoto, et al. 2013).

Regarding data, scholars use basic input-output tables published by national and regional statistical bureaus and water departments, as well as resources such as the National Economic Statistical Yearbook, the Water Resources Statistical Yearbook, and the Water Resources Bulletin, to prepare customized input-output tables. For example, the Water Resources Group of the Academy of Mathematics and Systems Science at the Chinese Academy of Sciences compiled 51-sectoral, national and Hai River basin water input-occupancy-output tables for 1999, 2002, and 2007 to study water use and efficiency, water-saving potential, shadow prices of water use, and industrial water demand.

Similar to the concept of the carbon footprint (S. Wang, Wang, and Yang 2018; Xin et al. 2014), international water flow has become an important research area (Chapagain and Hoekstra 2008; Hoekstra and Hung 2002, 2005; Y. Chen et al. 2020; Liu et al. 2020). Network analyses depict who trades water with whom and how the structure evolves over time (Konar et al. 2011; Dalin et al. 2012); while MRIO-based studies quantify embodied-water flows between countries and sectors and document how scarce water is

traded through global value chains (Lenzen, Moran, Bhaduri, Kanemoto, Bekchanov, Geschke, and Ward 2013).

Water footprint studies in consumption and production processes represent another important field. (Zhao et al. 2019) studied accounting of global grey water footprints, from both consumption and production perspectives. Those authors found that a cohort of BRIC countries (Brazil, Russia, India, and China) had a grey water production footprint (GWFP) larger than their grey water consumption footprint (GWFC)—accounting for over half of the global GWFP (53.6%)—mainly generated from domestic final-demand production. Alternatively, the OECD29 and EU27 groups of countries possessed GWFCs that exceeded their GWFPs.

Most studies on international virtual water flows are based on single countries, such as China (Y. Chen et al. 2020; He et al. 2020; Liu et al. 2020) or the USA (Konar and Marston 2020; Mubako, Lahiri, and Lant 2013), regional studies (Dalín et al. 2012; Zhao et al. 2019) or analysis of specific sectors such as crops (Hoekstra and Hung 2002, 2005), food (Dalín et al. 2012), farm animals (Mekonnen and Hoekstra 2012) or power supply (L. Wang et al. 2020). Such limitations reduce the value of the results because those approaches fail to capture the complete network of flows between nations. Furthermore, while much of this literature is measurement-focused, there remains a gap in terms of explaining cross-country *determinants* of net virtual water positions in a unified, global econometric framework—precisely the gap this paper addresses.

Within *Ecological Economics*, virtual water and water footprints have been used, for instance, as lenses to analyze how globalization redistributes water scarcity (Novo, Garrido, and Varela-Ortega 2009; Distefano and Kelly 2017), shapes comparative advantage (Reimer 2012), reflects power balances between states (Beltrán and Kallis 2018) and mediates trade-offs between economic development and ecological limits (Hachaichi 2023). Several contributions combine virtual-water accounting with trade theory (R. Chen et al. 2024; Duarte, Pinilla, and Serrano 2019) and MRIO techniques (Zhang and Diaz Anadon 2014; Oppon et al. 2018) to examine the economics of virtual-water trade and the role of water in structuring global production networks. Our paper complements this literature by moving from individual sectors or regions to a fully global, country-by-country MRIO system, and by explicitly linking countries' net virtual-water positions to trade structure, industrial composition, freshwater endowments, and macroeconomic performance in a unified framework.

Beyond accounting magnitudes, a strand of work links water footprints to *environmental management* instruments. ISO 14046 formalizes principles and requirements for water footprint assessment within life cycle thinking, while methodological advances, such as the AWARE characterization factors, allow managers to weight withdrawals by local scarcity in impact assessments (International Organization for Standardization 2014;

Boulay et al. 2018). Complementary LCA research proposes water *stress*-weighted footprints that better align with site-specific management priorities (Pfister, Koehler, and Hellweg 2009). At the system scale, the planetary boundaries framework highlights freshwater use as a global control variable for sustainable development (Rockström et al. 2009), while the water–energy–food (WEF) nexus emphasizes cross-sector coordination in policy and operations (Hoff 2011). For supply chains, MRIO has matured into a practical decision-support tool for corporate and public procurement footprinting, enabling managers to locate high–leverage tiers for efficiency and risk mitigation (Tukker and Dietzenbacher 2013; Wiedmann and Lenzen 2018). Recent work also connects virtual-water trade to hydrological risk transmission and resilience, underscoring the importance of sourcing strategies in water-stressed regions (D’Odorico et al. 2019).

2.2 The natural resource curse

Resource abundance has been associated with economic and political “curses” that may lower long-run economic growth and inhibit development. These ideas are captured by the natural resource curse (NRC) (Sachs and Warner 1995; Auty and Warhurst 1993; Auty and Furlonge 2019; Berman et al. 2017; Henry 2019). Early research focused on non-renewable resources (coal, oil, gas, and minerals) and emphasized mechanisms such as the Dutch disease (Corden 1984), exposure to price volatility and fiscal risk, enclave dynamics, and rent-seeking (Robinson, Torvik, and Verdier 2006). In ecological economics, these debates connect directly to questions about how resource dependence shapes structural change, institutional quality, distributional outcomes, and the long-run compatibility of growth with biophysical limits (Ploeg 2011; Badeeb, Lean, and Clark 2017).

The empirical record is mixed: influential critiques stress problems of *identification*—whether estimates identify a causal effect of resource abundance on economic growth rather than a mere correlation. Concerns include endogeneity from institutional quality, measurement (resource dependence vs. underlying endowment), and omitted variables such as geography or colonial history (Alexeev and Conrad 2009; Mehlum, Moene, and Torvik 2006; Brunnschweiler and Bulte 2008). Complementing these debates, survey articles synthesize channels and evidence by organizing the literature’s mechanisms—economic (e.g., Dutch disease and volatility), political (e.g., institutional erosion, corruption and conflict), and social/human-capital (e.g., inequality and education)—and assessing the weight of empirical support for each argument (Ploeg 2011; Badeeb, Lean, and Clark 2017). Cross-country experience also indicates that strong institutions can offset—or even reverse—curse dynamics.

Historical evidence is often interpreted as supporting the NRC, which is closely tied to the geographic distribution of resources. For instance, Japan, South Korea, and

Singapore—countries with few exportable natural resources—have achieved the living standards of developed nations (Akkemik 2009; E. K. Y. Chen 1979). Alternatively, many countries in Africa, the Middle East, and South America, despite being rich in natural resources such as oil and minerals, have exhibited weak economic performance (Badeeb, Lean, and Clark 2017; Muhanji, Ojah, and Soumaré 2019; Ploeg 2011). Consistent with proposed channels, the literature identifies five pathways through which resource abundance might hinder development. First, significant price fluctuations expose resource-dependent states to extreme vulnerabilities in increasingly financialized global markets; speculative activity in commodity derivatives can amplify fiscal stress and default risk (Clapp 2012; Bakhsh and Zhang 2023). Second, resource booms can appreciate the real exchange rate and crowd-out tradable sectors—the classic Dutch disease mechanism (Corden 1984; Cust, Harding, and Vézina 2019).

Third, scholars have identified an enclave effect (Phelps, Atienza, and Arias 2015), where a dominant natural resource sector becomes isolated from the rest of the economy (e.g., specialized infrastructure and foreign labor). This detachment, coupled with the sector's macro weight, may weaken incentives to invest in broad-based capabilities (e.g. education or non-resource capital). Fourth, rent-seeking can dominate in weak-institutional settings (Auty and Furlonge 2019; Wick and Bulte 2006), with political leaders using resource rents to lower taxes, raise transfers, and reward patrons, often at the expense of diversification (Hancock and Sovacool 2018; Robinson, Torvik, and Verdier 2006). In such contexts, autocrats may deploy rents to entrench power (Mesquita et al. 2003), although links between resources and authoritarianism remain debated (Brooks and Kurtz 2016; Haber and Menaldo 2011). Fifth, competition over resource control can trigger civil unrest or military conflict (Le Billon 2013).

The NRC concept has been extended to water resources. In a notable article, (Hancock and Sovacool 2018) argued that causal mechanisms driving the NRC could be applied to countries with sufficient water resources to develop large-scale hydropower or other water-intensive projects. With respect to price fluctuations, they suggested that a water-based NRC might emerge through volatility in electricity revenues from hydropower; they cited Laos as an example where an abundance of water, and large-scale power exports, inflated the exchange rate and hampered economic growth. They further noted enclave characteristics (specialized expertise and external finance) and the potential for rent-seeking in capital-intensive dam construction. For ecological economics, these arguments raise a broader question: when economies pursue water-intensive development strategies (for example, through hydropower or green industrialization), do these paths systematically undermine long-run well-being, or can appropriate institutions and policies align resource abundance with sustainable development?

Nevertheless, the NRC has faced criticism. (Alexeev and Conrad 2009) argued that NRC results can hinge on sample periods and measurement, while (Manzano and Rigobon

2001) contended that the findings largely reflected the oil price surge of the 1970s and 1980s. Others stressed that institutional quality mediates outcomes: with strong institutions, resource abundance need not be a curse and may be a *blessing* (Mehlum, Moene, and Torvik 2006; Brunnschweiler and Bulte 2008; Ploeg 2011). This debate motivates our focus on whether *water abundance*, proxied through renewable inland freshwater endowments and persistent net *virtual-water* exports, predicts weaker economic growth at the country level once trade structure and industrial composition are incorporated. In contrast to project-level hydropower case studies, our empirical strategy leverages global MRIO evidence to test for a water-specific resource curse in the aggregate, while treating GDP growth as one—but not the only—indicator of development paths.

Environmental management studies suggest governance and policy levers that can attenuate putative curse mechanisms in water-intensive contexts. Integrated water resources management (IWRM) stresses basin-scale coordination across sectors and users (Global Water Partnership 2000; Biswas 2004), while economic instruments—especially volumetric pricing and tariff reform—can deliver substantial conservation at lower cost than non-price mandates in urban settings (Olmstead and Stavins 2009). In supply chains, disclosure frameworks and footprinting standards (e.g., ISO 14046) enable firms and public agencies to identify priority suppliers and invest in process changes and demand-side management, where local scarcity renders marginal water particularly valuable (International Organization for Standardization 2014; Boulay et al. 2018). These management-oriented insights motivate our empirical focus on trade structure and industrial composition as proximate drivers of embodied-water balances, and connect our MRIO estimates to actionable levers—efficiency upgrades, input substitution, and sourcing diversification—available to regulators and firms.

3. Analytical framework

We develop a concise open-economy mechanism that links trade structure, industrial composition, and water endowments to countries' NVW positions and to a reduced-form relationship with economic growth. The framework provides a transparent bridge between global MRIO accounting and management-relevant indicators, such as exposure to external water and reliance on imported intermediates.

3.1 Environment and water use

Countries are indexed by $i = 1, \dots, N$. Each country has a renewable inland water endowment \bar{R}_i . Sectoral output Y_{si} (e.g., agriculture, manufacturing and services) uses a direct water requirement a_{si} per unit of gross output, with the national feasibility condition

$$\sum_s a_{si} Y_{si} \leq \bar{R}_i, \quad (3.1)$$

and shadow value $\lambda_i \geq 0$ on the water constraint. When the constraint is slack, $\lambda_i = 0$. This assumption mirrors standard IO feasibility and environmental extensions and is consistent with water-footprint accounting frameworks (Leontief 1970; Miller and Blair 2009; Hoekstra and Hung 2005; Hoekstra and Mekonnen 2012). Intuitively, λ_i summarizes the marginal cost of scarce water; when scarcity is low, λ_i is near zero.

3.2 MRIO-consistent virtual-water accounting

Let W_{ij} denote the virtual water used in i to satisfy final demand in j . With ω_i^\top the (direct+indirect) water coefficients implied by the Leontief inverse (cf. Eq. (4.4)) and \mathbf{Y}_{ij} the final-use vector in j sourced from i ,

$$W_{ij} = \omega_i^\top \mathbf{Y}_{ij}, \quad (3.2)$$

and country-level net positions are

$$\text{NVW}_i \equiv \sum_j W_{ij} - \sum_j W_{ji}. \quad (3.3)$$

Eqs. (3.2)–(3.3) nest the MRIO construction (see Eq. (4.5)) used to compute bilateral embodied-water flows; see Leontief (1936); Miller and Blair (2009); Wiedmann et al. (2007); Lenzen, Moran, Kanemoto and Geschke (2013); Lenzen, Moran, Bhaduri, Kanemoto, Bekchanov, Geschke and Ward (2013); Allan (1993). NVW_i summarizes whether a country is a net externalizer or absorber of water through trade.

3.3 Trade structure

Final-demand absorption follows an Armington CES across origins. With p_i the f.o.b. producer price (or price index) in origin i , $\tau_{ij} \geq 1$ an iceberg trade cost from i to j (so the delivered price in j is $p_i \tau_{ij}$), $\phi_i > 0$ a supply/composition shifter (capacity/variety/quality), and $\sigma > 1$ the elasticity of substitution, the share of market j 's expenditure allocated to origin i is

$$s_{ij} = \frac{(p_i \tau_{ij})^{-\sigma} \phi_i}{\sum_k (p_k \tau_{kj})^{-\sigma} \phi_k}, \quad (3.4)$$

so $s_{ij} \in [0,1]$ and $\sum_i s_{ij} = 1$ for each j (Armington 1969). Let $\mathbf{Y}_{\cdot j} \equiv \sum_k \mathbf{Y}_{kj}$ denote market j 's final-use vector; absorption from i is then $\mathbf{Y}_{ij} = s_{ij} \mathbf{Y}_{\cdot j}$. Aggregate exports and imports proxy $\sum_j \mathbf{Y}_{ij}$ and $\sum_j \mathbf{Y}_{ji}$, respectively. Armington shares bridge trade costs and prices to bilateral absorption and, via (3.2), to embodied-water flows; see (Anderson and Wincoop 2003; Eaton and Kortum 2002).

3.4 Comparative statics

We work with *absorption-based* (final-demand) trade aggregates consistent with (3.2) and (3.4). Let ι be a conformable vector of ones and recall that \mathbf{Y}_{ij} is market j 's final-use vector sourced from origin i . Define

$$\text{Exports}_i^{\text{FD}} \equiv \iota^\top \sum_j \mathbf{Y}_{ij}, \quad \text{Imports}_i^{\text{FD}} \equiv \iota^\top \sum_j \mathbf{Y}_{ji},$$

so that changes in $\{\text{Exports}_i^{\text{FD}}, \text{Imports}_i^{\text{FD}}\}$ map one-for-one into embodied-water flows W_{ij} via (3.2) and (3.4) (Armington 1969; Miller and Blair 2009). Differentiating the NVW identity (3.3) around a steady state yields:

$$\begin{aligned} \frac{\partial \text{NVW}_i}{\partial \ln \text{Exports}_i^{\text{FD}}} &> 0 \text{ Exports raise net outflows,} \\ \frac{\partial \text{NVW}_i}{\partial \ln \text{Imports}_i^{\text{FD}}} &< 0 \text{ Imports raise net inflows.} \end{aligned}$$

Next, let ShareM_i denote manufacturing's value-added share of GDP, constructed from the MRIO value-added vector v_{si} as

$$\text{ShareM}_i \equiv \frac{\sum_{s \in \mathcal{M}} v_{si}}{\sum_s v_{si}},$$

where \mathcal{M} indexes manufacturing sectors under the MRIO's native mapping. Let μ_i be manufacturing's imported-intermediate share,

$$\mu_i \equiv \frac{\text{Imported intermediates used by manufacturing in } i}{\text{Total intermediates used by manufacturing in } i},$$

which is computed from the MRIO use table by partitioning the manufacturing block and restricting origins to $k \neq i$. When manufacturing relies on imported intermediates whose partners exhibit above-average embodied-water intensities, a small-change argument gives

$$\frac{\partial \text{NVW}_i}{\partial \text{ShareM}_i} \approx -\mu_i \cdot \tilde{\omega}^{\text{partners}} < 0, \quad (3.6)$$

where $\tilde{\omega}^{\text{partners}}$ is the import-weighted mean of partners' embodied-water intensities for manufacturing intermediates. Increased reliance on imported inputs from water-intensive suppliers tends to raise NVW inflows.

For endowments, if the water constraint is slack ($\lambda_i = 0$), first-order terms cancel and

$$\frac{\partial \text{NVW}_i}{\partial \ln \bar{R}_i} \approx 0, \quad (3.7)$$

so water abundance does not mechanically predict net outflows—consistent with water-footprint/IO logic (Hoekstra and Mekonnen 2012; Leontief 1970) and in contrast to resource-curse priors (Sachs and Warner 1995, 2001). In practice, this observation implies that policy and trade structure, not endowment levels alone, determine NVW outcomes.

Robustness (BoP totals). As a high-level alternative to the FD aggregates, we also use Balance-of-Payments (BoP) goods+services totals under the IMF BPM6 framework². Define

$$\text{Exports}_i^{\text{BOP}} \equiv \text{Credits}_i(\text{Goods}) + \text{Credits}_i(\text{Services}),$$

$$\text{Imports}_i^{\text{BOP}} \equiv \text{Debits}_i(\text{Goods}) + \text{Debits}_i(\text{Services}),$$

In other words, as current-account totals on a *change-of-ownership* basis (merchandise recorded in goods; processing without ownership change recorded as services). Estimates using $\{\text{Exports}_i^{\text{BOP}}, \text{Imports}_i^{\text{BOP}}\}$ deliver the same signs and similar magnitudes as the FD baseline; we retain FD because it aligns directly with Eqs. (3.3) and (3.4) and with MRIO-consistent W_{ij} .

3.5 Economic growth relationships

We close the mechanism with a reduced-form link from embodied-water trade to economic growth:

$$g_i \equiv \frac{\dot{Y}_i}{Y_i} \approx g_{A,i} + \psi \cdot \text{NVW}_i^{\text{inflow}} - \chi \lambda_i,$$

where $g_{A,i}$ is *total factor productivity (TFP) growth*—the Solow residual³. The parameter $\psi \geq 0$ summarizes the contribution of imported, water-embodied intermediates to productivity, and $\chi > 0$ is the marginal cost of a binding water constraint, with $\lambda_i \geq 0$ the shadow value from (3.1). Define gross outflows and inflows $O_i \equiv \sum_j W_{ij}$ and $I_i \equiv \sum_j W_{ji}$, so that $\text{NVW}_i = O_i - I_i$. We measure the net-inflow component as the positive part

$$\text{NVW}_i^{\text{inflow}} \equiv (I_i - O_i)^+ = \max\{I_i - O_i, 0\},$$

so $\text{NVW}_i^{\text{inflow}} > 0$ only when i is a net *importer* of embodied water.

² BPM6 = IMF *Balance of Payments and International Investment Position Manual*, 6th ed.

³ In growth-accounting terms, $g_{A,i} = g_{Y,i} - \sum_x s_{x,i} g_{x,i}$ with $x \in \{K, L, M, E, \dots\}$ and $s_{x,i}$ the input cost shares.

For the empirical analysis, we work with *intensities* so that coefficients are comparable across economies of different sizes:

$$\widetilde{\text{NVW}}_i^{\text{inflow}} \equiv \frac{\text{NVW}_i^{\text{inflow}}}{Y_i} \quad \text{or} \quad \frac{\text{NVW}_i^{\text{inflow}}}{\sum_s a_{si} Y_{si}},$$

the latter normalizing by domestic water use. In (3.8) we substitute the chosen intensity for $\text{NVW}_i^{\text{inflow}}$.

In terms of economic channels, the ψ term captures two related mechanisms. First, imported intermediates can embody higher-quality technologies, greater product variety, and process innovations that raise productivity in domestic production (Amiti and Konings 2007; Halpern, Koren, and Szeidl 2015; Goldberg et al. 2010). Second, when water-intensive stages of production are located abroad, domestic water stress is alleviated, effectively expanding feasible output for a given endowment \bar{R}_i . The $-\chi\lambda_i$ term captures the opposite force: when the water constraint binds (complementary slackness $\lambda_i(\bar{R}_i - \sum_s a_{si} Y_{si}) = 0$), marginal water is costly and economic growth is dampened. If $\lambda_i \approx 0$ in most country–years, the mechanism does not imply a general economic growth penalty from water abundance or from NVW inflows (cf. Sachs and Warner 2001).

In the baseline regressions, we use MRIO-consistent W_{ij} to form I_i and O_i , and we lag the intensity term (e.g. $t - 1$) to mitigate simultaneity. We report (i) the truncated net inflow $\widetilde{\text{NVW}}_i^{\text{inflow}}$ and (ii) a symmetric alternative using *gross* inflows I_i/Y_i (no truncation). Heterogeneity is assessed via interactions with the imported-intermediate share μ_i (strength of the productivity channel) and with water-stress proxies λ_i (likelihood that the water constraint binds). The model implies $\psi \geq 0$ and $\chi > 0$: effects are expected to be stronger where μ_i is large and where λ_i is high (scarcity), and weaker where $\lambda_i \approx 0$ (low stress / high water abundance). We also examine heterogeneity by water *abundance*, proxied by NVW inflows I_i/Y_i (cf. Amiti and Konings 2007; Halpern, Koren, and Szeidl 2015; Sachs and Warner 2001).

3.6 Testable implications

The mechanism yields the following testable implications, which are relevant for economic analysis and environmental management:

- **H1 (Manufacturing and inflows).** Countries with a larger manufacturing share of value added exhibit higher NVW inflows, reflecting greater reliance on imported intermediates from water-intensive suppliers [Eq. (3.6)].
- **H2 (Income and inflows).** At lower development levels, higher GDP per capita is associated with higher NVW inflows, with the relationship weakening or

reversing as embodied-water intensities ω_i fall and export composition upgrades (mechanism discussion above).

- **H3 (Exports and outflows).** Higher exports are associated with higher NVW outflows [Eq. (3.5)].
- **H4 (Imports and inflows).** Higher imports are associated with higher NVW inflows [Eq. (3.5)].
- **H5 (Endowments and outflows).** Conditional on trade structure, industrial composition, and income, renewable freshwater endowments are not systematically associated with higher NVW outflows when the water constraint is slack [Eq. (3.7)]. In other words, endowment levels alone need not determine NVW export status.
- **H6 (Economic growth and “water curse”).** NVW inflows are not associated with lower economic growth; when water constraints are not binding, they may be (at most) weakly growth-enhancing through the productivity channel captured by ψ [Eq. (3.8)]. Thus the mechanism does not imply a generic “water resource curse” at the macro level.

In the econometric analysis that follows, we map these hypotheses into regression specifications, linking the MRIO-based accounting to both economic outcomes (net NVW positions and growth) and management levers, such as sourcing choices, efficiency improvements, and supply-chain risk management.

4. Methods

4.1 Data sources

Our primary source is the Eora multi-region input–output database (Eora26), which reports harmonized annual MRIO tables for 189 countries plus a Rest-of-World (ROW) account. For each year across a 2010–21 timeframe, we use the standard MRIO components—the intermediate transactions matrix \mathbf{T} , the final demand matrix \mathbf{Y} , and the value-added matrix \mathbf{V} —together with Eora’s environmental satellite account \mathbf{Q} for water. The satellite reports sectoral blue/green/grey water footprints; we aggregate these components into a single total to construct country-level embodied-water coefficients consistent with the MRIO (see Table A.2, Appendix A).

Coverage in \mathbf{Q} is incomplete for roughly one-fifth of country–year cells. To close gaps, we drew on two auxiliary sources: (i) FAO AQUASTAT (national water withdrawals by sector) and (ii) World Bank World Development Indicators (WDI; renewable freshwater resources, total withdrawals, and use shares). We aligned definitions with the Eora

sectoring, interpolated within each source when short gaps occurred, and then built country–year water-use vectors by allocating national totals across sectors using the most recent observed sectoral shares. When multiple recent observations were available (WDI typically through 2018; AQUASTAT to 2010), we computed a country-specific mean of the latest years as a stable proxy and scaled the sectoral vector to match national totals. Finally, we rescaled imputed vectors to ensure consistency with MRIO production totals and dropped the ROW account from estimation. Robustness checks using alternative interpolation (last/next observation carried forward) and alternative scaling schemes yield substantively similar results (see also Table A.4, Appendix A).

4.2 Data processing

Eora26 provides a country–sector MRIO for 189 countries (26 sectors each) plus a Rest-of-World (ROW) account. The intermediate matrix \mathbf{T} has a dimension of 4915×4915 (189×26 country–sector rows/columns plus one ROW account), and \mathbf{Y} stacks six final-use categories per country. Because our analysis focuses on between-country virtual-water flows—rather than sectoral detail—we collapse the sector dimension and construct country-by-country use matrices. Specifically, for countries $i, j \in \{1, \dots, 189\}$ and sectors $s, r \in \mathcal{S}$ (with $|\mathcal{S}| = 26$), we aggregate blocks as

$$Z_{ij} = \sum_{s \in \mathcal{S}} \sum_{r \in \mathcal{S}} T_{(i,s),(j,r)}, \quad Y_{ij}^F = \sum_{s \in \mathcal{S}} \sum_{c \in \mathcal{C}} Y_{(i,s),(j,c)},$$

where \mathcal{C} indexes final-demand categories. This yields a 189×189 matrix \mathbf{Z} of intermediate deliveries from i to j and a 189×189 matrix \mathbf{Y}^F of final goods and services from i absorbed in j . The ROW account is excluded from the econometric analysis to avoid compositing heterogeneity.

The environmental satellite account \mathbf{Q} reports sectoral water footprints as blue (surface and groundwater), green (soil moisture), and grey (dilution requirement). In the baseline, we sum these components to obtain sectoral totals and then aggregate to the country level:

$$w_i = \sum_{s \in \mathcal{S}} (q_{is}^{\text{blue}} + q_{is}^{\text{green}} + q_{is}^{\text{grey}}),$$

producing a 1×189 vector \mathbf{w} of total water use consistent with the MRIO (Component-specific results are reported as robustness checks in the Appendix). The WDI database also distinguishes blue/green/grey water at the national level, whereas FAO AQUASTAT reports withdrawals by sector (not by the three footprint components); in all cases we harmonize definitions to the Eora sectoring before aggregation.

For flow accounting, we retain the full 189×189 Eora system. For analyses requiring WDI covariates, we work with the set of countries covered by the World Bank: Appendix Table A.1 lists the 185 countries for which the WDI series are available. However, four countries lack a complete set of macro controls, so the baseline regressions are estimated on 181 countries. Table 1 summarizes the key variables used in the econometric analysis; nominal series are converted to constant prices following WDI guidance, and country identifiers are harmonized to ISO3.

Table 1: Summary statistics of key variables

	Samples	Average	Sd	min	max
GDP growth rate (annual percentage)	2,146	2.904	5.847	-54.336	86.827
GDP per capita (constant 2010 dollars, ten thousand dollars)	2,172	1.824	2.774	0.021	22.382
Exports of goods and services (2010 constant dollars, Trillion)	1,988	0.133	0.331	0.000	3.555
Imports of goods and services(2010 constant dollars, Trillion)	1,949	0.134	0.340	0.000	3.415
Resident final consumption expenditure (2010 constant dollars, Trillion)	1,928	0.359	1.404	0.001	19.489
Net foreign direct investment (2010 constant dollars, Trillion)	1,981	-0.001	0.028	-0.345	0.218
Renewable inland freshwater resources per capita (cubic meters, ten thousand)	2,036	1.595	4.914	0.000	53.452
Manufacturing, value added (% of GDP)	2,014	11.891	6.433	0.336	38.809

Data source: World Bank WDI (World Development Indicators), <https://wdi.worldbank.org>.

To frame the accounting, Table 2 sketches a standard non-competitive inter-regional input–output table for n regions, with intermediate uses, final uses, value added, and a satellite account for water. We use “region” for consistency with MRIO notation; throughout this term is interchangeable with “country.”

Table 2: Structure of the multi-region input-output table

		Intermediate use				Final Use				Total Output
		Regio n 1	Regio n 2	...	Regio n n	Regi on 1	Regi on 2	...	Regio n n	

Intermediate use	Region 1	z^{11}	z^{12}	...	z^{1n}	y^{11}	y^{12}	...	y^{1n}	x^1
	Region 2	z^{21}	z^{22}	...	z^{2n}	y^{21}	y^{22}	...	y^{2n}	x^2
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Region n	z^{n1}	z^{n2}	...	z^{nn}	y^{n1}	y^{n2}	...	y^{nn}	x^n
Primary input (value added)		v^1	v^2	...	v^n					
Total input		x^1	x^2	...	x^n					
Water resource occupation		w^1	w^2	...	w^n					

In this notation, z_{ij} denotes intermediate inputs from region i used in region j ; y_{ij} denotes final uses in region j sourced from region i ; x_i is total output in region i ; v_i is value added; and w_i records water use. These objects correspond to the accounting set-up in Section 3 and feed into the MRIO calculation in Section 4.3 (Eq. (4.5)) used in the results that follow.

4.3 MRIO model construction

Consistent with the MRIO described above, let \mathbf{T} collect intermediate uses and \mathbf{Y} collect final uses across n regions (countries). Using block notation where the (i, j) block stacks flows from region i to region j across sectors,

$$\mathbf{T} = \begin{bmatrix} z^{11} & z^{12} & \dots & z^{1n} \\ z^{21} & z^{22} & \dots & z^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z^{n1} & z^{n2} & \dots & z^{nn} \end{bmatrix}, \quad \mathbf{Y} = \begin{bmatrix} y^{11} & y^{12} & \dots & y^{1n} \\ y^{21} & y^{22} & \dots & y^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y^{n1} & y^{n2} & \dots & y^{nn} \end{bmatrix}. \quad (4.1)$$

Let \mathbf{V} denote value added and \mathbf{Q} the environmental satellite account for water, both aggregated to the country level for our between-country analysis:

$$\mathbf{V} = [v^1 \quad v^2 \quad \dots \quad v^n], \quad \mathbf{Q} = [w^1 \quad w^2 \quad \dots \quad w^n]. \quad (4.2)$$

Define the matrix of direct input (technical) coefficients by pre-multiplying each use block by the inverse of total output of the using region. Let x^j be the vector of gross output in region j and $\hat{x}^j \equiv \text{diag}(x^j)$ the associated diagonal matrix. Then

$$\mathbf{A} = \begin{bmatrix} A^{11} & A^{12} & \dots & A^{1n} \\ A^{21} & A^{22} & \dots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \dots & A^{nn} \end{bmatrix}, \quad A^{ij} = z^{ij}(\hat{x}^j)^{-1}, \quad (4.3)$$

so A^{ij} gives the inputs sourced in i per unit of output produced in j .

The global Leontief inverse summarizes direct and indirect requirements:

$$\mathbf{B} = \begin{bmatrix} B^{11} & B^{12} & \dots & B^{1n} \\ B^{21} & B^{22} & \dots & B^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ B^{n1} & B^{n2} & \dots & B^{nn} \end{bmatrix} = (\mathbf{I} - \mathbf{A})^{-1}. \quad (4.4)$$

To compute embodied (virtual) water used in region i to satisfy final demand in region j , we weight total requirements by country-level water use. Let $\text{diag}(w^1, \dots, w^n)$ form a block-diagonal matrix that places each country's water vector on the diagonal (conformable with \mathbf{B}). The bilateral embodied-water matrix is then

$$\mathbf{W} = \text{diag}(w^1, \dots, w^n) \mathbf{B} \mathbf{Y}, \quad (4.5)$$

where the (i, j) block W^{ij} gives virtual water extracted in region i that is ultimately absorbed as final demand in region j . Country-level net positions follow by summing rows and columns of \mathbf{W} (excluding own use) to obtain net outflows (exports) and inflows (imports) of virtual water.

5. Results

5.1 Virtual-water flows

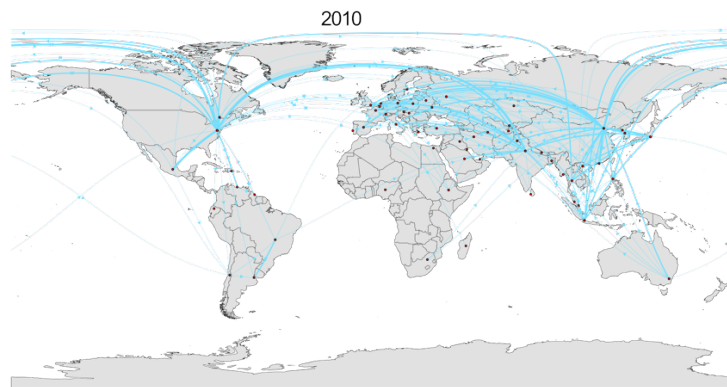
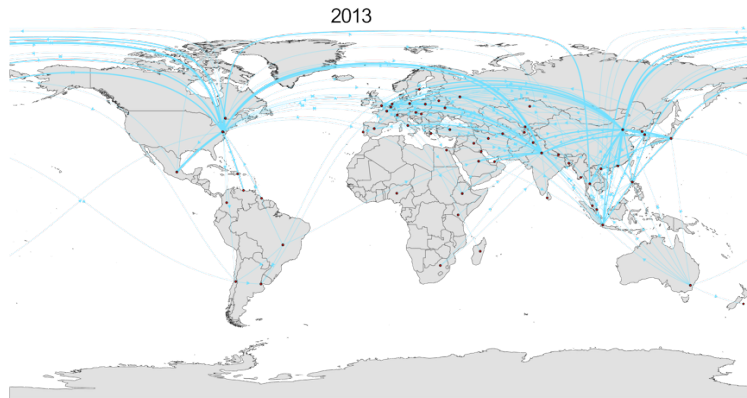
Using the multi-region input-occupancy-output framework, we computed the bilateral embodied-water matrix \mathbf{W} from Eq. (4.5) for 189 countries. Figure 1 provides harmonized snapshots for 2010, 2013, 2017, and 2021, reporting the top-twenty net exporters and net importers of virtual water (Bm^3).

Global patterns highlight the role of scale and geography. Countries with large populations and/or territory—most notably the U.S., China, and India—occupy central positions in the network (Figure 1). Advanced economies in North America and Europe tend to be the primary virtual-water exporters, whereas many Asian economies appear as leading importers. From an environmental management perspective, these patterns identify where supply-chain water use is externalized or absorbed.

These patterns reflect underlying specialization. The U.S., as one of the world's largest agricultural exporters, dominates virtual-water outflows, primarily through crop trade to populous markets such as China, India, and Mexico. Conversely, China and India rank among the top virtual-water importers. This data reflects substantial food demand, industrial structures that rely on imported water-intensive agricultural products and intermediate inputs, and sizeable manufacturing exports.

Virtual-water flows also exhibit pronounced spatial clustering. Dense regional links arise within North America (e.g., U.S.–Mexico), Asia (e.g., China–Vietnam), and Europe. This agglomeration is consistent with shared agro-climatic conditions, lower bilateral trade costs over short distances, and the presence of regional trade agreements that deepen intra-regional exchange. For managers and policymakers, such clustering highlights regional leverage points for efficiency gains and risk mitigation.

Finally, we observe a notable reorientation over the period: the dominant U.S.–China corridor in the early part of the sample (e.g., 2010) is overtaken by U.S.–India flows by 2021, coinciding with escalating U.S.–China trade tensions. This reorientation illustrates how trade-policy realignments can redirect embodied-water routes even when aggregate demand for water-intensive goods remains strong, reinforcing the need to monitor sourcing exposure over time.



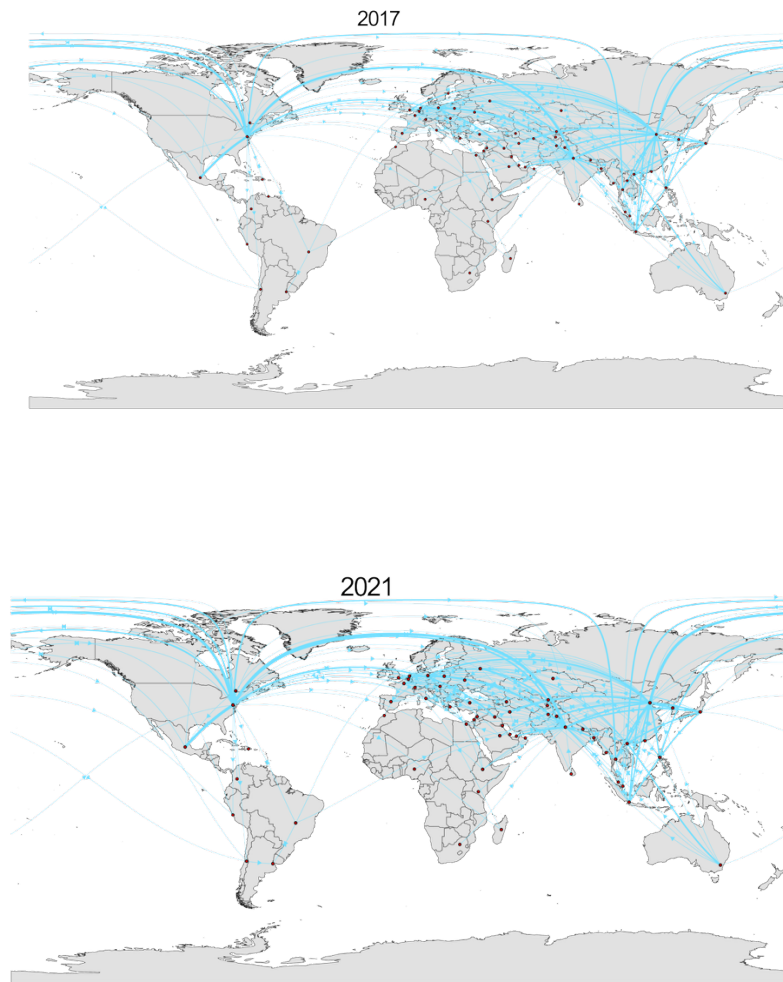


Figure 1: Virtual water flows between 189 countries.

Notes. (1) Country totals are obtained from the flow matrix by summing rows (outflows) and columns (inflows) and excluding own use. (2) Arrows indicate flow direction (source → destination); line thickness is proportional to volume. (3) To reduce clutter, only links of at least 500 million m³ are shown.

From a macro perspective, across our 2010–21 timeframe, net positions align with specialization and income. Developed economies consistently dominate *net outflows* of virtual water, reflecting comparative advantage in primary commodities and the water content of complex manufactures, whereas many developing economies appear as *net importers*. The U.S. is the largest net exporter, with annual outflows exceeding 7 Bm³, driven primarily by agriculture-embodied exports. By contrast, industrialized economies such as Germany and Japan achieve net exports via high-value manufacturing, despite limited agricultural resources. On the import side, several rapidly growing economies—

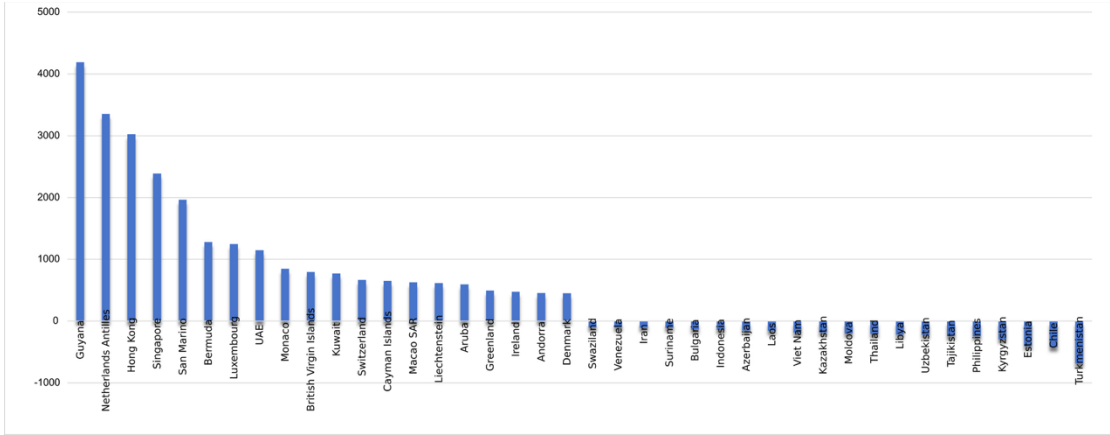
India, Vietnam, and Indonesia—repeatedly appear among the largest NVW importers, particularly by 2021, reflecting reliance on water-intensive food and intermediate inputs.

For environmental economists, these patterns illustrate how trade reallocates water use across basins: exporters bear the opportunity cost and ecological impacts of water extraction, while importers effectively draw on external water endowments and associated risks. Whether this reallocation is welfare-enhancing depends on relative scarcity, pricing, and institutions. The split suggests different policy levers: efficiency and stewardship along export supply chains for net exporters, and sourcing diversification, demand-side measures, and risk-informed procurement for net importers.

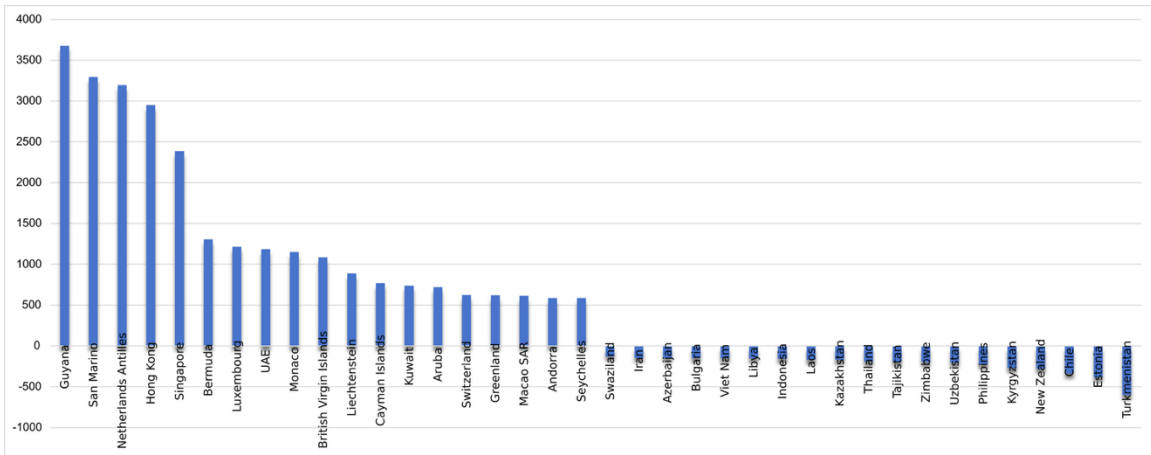
The spatial distribution of national net flows reflects interactions among endowments, industrial structure, and value-chain position. In water-scarce countries (e.g., Egypt and Iran), constrained agricultural capacity necessitates sustained imports of water-intensive staples (e.g., cereals), generating a *resource-constrained inflow* pattern. China’s trajectory illustrates upgrading: over the 2010–21 period, net inflows declined as the export mix shifted from textiles/agri-products toward more water-efficient machinery. Trade hubs such as Hong Kong and Singapore maintain persistent net outflows, despite negligible freshwater endowments, by leveraging nodal positions in global supply chains and re-exports—demonstrating how services and logistics can reconfigure physical resource flows.

Because aggregate net flows are mechanically larger for more populous economies, cross-country comparisons based on totals alone can be misleading. To complement these totals, we, therefore, construct *per-capita* NVW positions by dividing each country’s NVW flow by its population, using WDI population data for 2010, 2013, 2017, and 2021 (Figure 2). Appendix Figure A.3 reports the corresponding total NVW flow rankings by country for completeness.

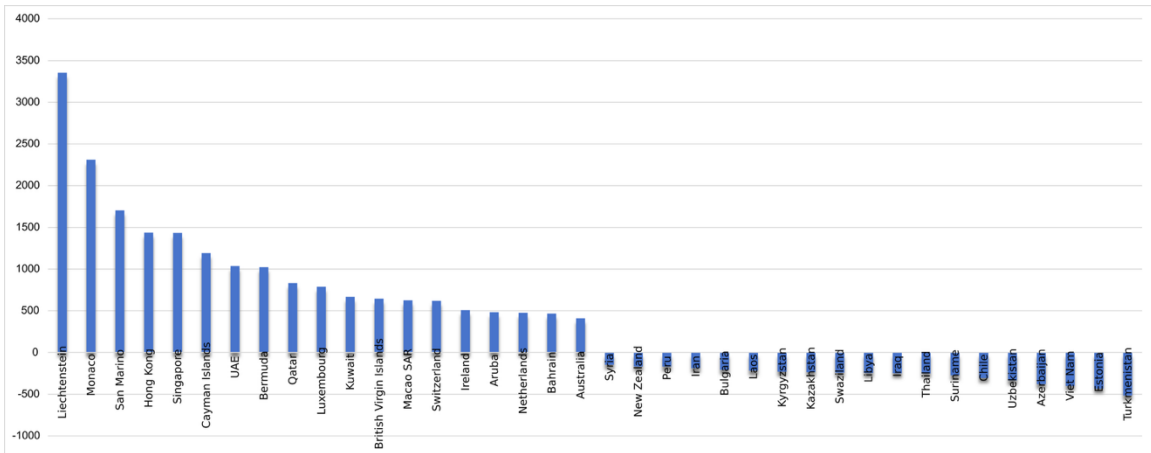
A clear dichotomy emerges: small, open economies often display very high per-capita net outflows via two archetypes—(i) services/trade hubs (e.g., Singapore and Hong Kong) transmitting embodied water through re-exports and high-value services; and (ii) resource-dependent exporters (e.g., UAE and Qatar) that externalize domestic water scarcity through trade. Conversely, rapidly industrializing economies (e.g., Vietnam, the Philippines and Indonesia) exhibit substantial per-capita net inflows; for instance, Vietnam’s per-capita inflow reached about 418 m³ in 2021 (an increase of approximately 27% since 2010). Because per-capita rankings remove the mechanical effect of country size and bring small, highly open economies to the foreground, they are best interpreted as complements to aggregate flows. Overall, these patterns point to trade structure and industrial composition—rather than freshwater endowments alone—as proximate correlates of countries’ virtual-water balances.



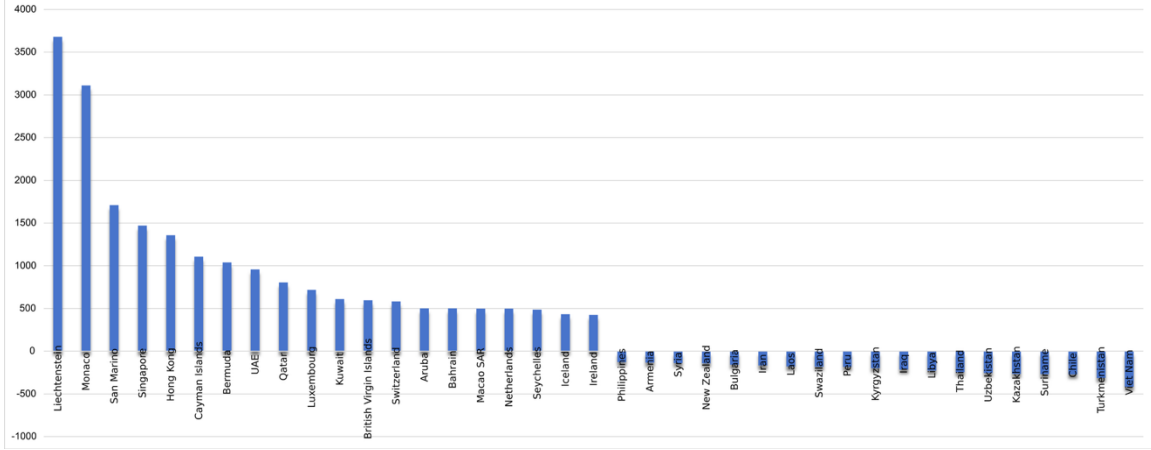
(i) 2010



(ii) 2013



(iii) 2017



(iv) 2021

Figure 2: Per-capita NVW flow ranking by country. For each year, the histograms show the 20 countries with the largest per-capita net outflows and the 20 countries with the largest per-capita net inflows.

The *per-capita* pattern thus reinforces how *openness and specialization* (rather than water endowment alone) drive large outflows in small economies, whereas *industrialization and value-chain positioning* underpin inflows in fast-growing, populous economies. While richer countries often appear as per-capita net exporters and lower-income countries as per-capita net importers, prominent exceptions caution against a simple income gradient; the association weakens once trade structure and industrial composition are considered. Accordingly, the per-capita rankings are best read as a complement to aggregate flows, emphasizing the role of economic structure in shaping virtual-water balances and informing sourcing and efficiency priorities.

5.2 Determinants of net virtual-water outflow

Figures 1 and 2 document salient features of the global embodied-water network. To move from description to inference, we translate the bilateral matrix \mathbf{W} in Eq. (4.5) into country-year net positions. For each country i , the net virtual-water outflow is

$$NVW_i = \sum_j W_{ij} - \sum_j W_{ji},$$

and the corresponding adjacency matrix \mathbf{M} collects the off-diagonal bilateral flows ($i \neq j$). These objects provide the dependent variable and bilateral structure for our econometric tests.

We then merge NVW_i with the covariates listed in Table 1—exports, imports, manufacturing share, GDP per capita and economic growth, and renewable freshwater measures—to quantify how trade structure, industrial composition, income, and

endowments relate to countries' net virtual-water positions (and, in turn, to economic growth in the NRC specification). Summary statistics for the flow variable are reported in Table 3. As expected from accounting identities, the cross-section mean of net flows is (approximately) zero, while dispersion is substantial (units: Bm^3), reflecting wide heterogeneity in specialization and value-chain roles. These variables feed into the regression models below.

Table 3: Summary statistics: net virtual-water outflow, country-year observations (Bm^3)

	N	Mean	SD	Min	Max
Net virtual-water outflow	2,220	-0.0069	10.6256	-85.6078	77.8320

Notes: Values are across country-year observations; outflow is defined as embodied-water exports minus embodied-water imports. Units: billion cubic meters (Bm^3). The mean is approximately zero as implied by the accounting identity (global net flows sum to zero each year).

Source: authors' calculations from MRIO-based embodied-water accounting.

We take net virtual-water outflow (NVW_i ; embodied-water exports minus imports, in Bm^3) as the dependent variable and relate it to trade structure, industrial composition, income, and endowments using OLS. Explanatory variables are listed in Table 1. Sample size varies by specification due to data availability. Results are reported in Table 4.

Across specifications, the signs align with the mechanism: exports are positively associated with net outflows, imports negatively so; a larger manufacturing share is linked to net inflows; GDP per capita enters with a negative coefficient in all three models; and renewable freshwater per capita is not a robust predictor of net outflows. Resident consumption expenditure loads positively (a scale effect), and FDI is positive where included. Overall, **H1–H4** are supported, and the results are consistent with **H5** (we do not reject it).

Table 4: Determinants of net virtual-water outflow (OLS)

	Model 1	Model 2	Model 3
GDP per capita	-0.539*** (-3.205)	-0.420** (-2.459)	-0.837*** (-4.548)
Resident final consumption expenditure	6.878*** (28.965)	7.063*** (29.200)	6.789*** (17.875)
Renewable inland freshwater resources per capita	-0.0103 (-0.047)	0.120 (0.523)	-0.0965 (-0.415)
Net foreign direct investment		25.23*** (10.143)	

	Model 1	Model 2	Model 3
Manufacturing value added (% GDP)		-0.227*** (-5.173)	
Exports of goods and services			15.08*** (4.641)
Imports of goods and services			-12.78*** (-3.323)
Constant	-1.878*** (-4.398)	0.428 (0.632)	-1.704*** (-3.636)
	<i>N</i>	1801	1650
	<i>R</i> ²	0.341	0.398
			1699
			0.353

Notes: Dependent variable is net virtual-water outflow (Bm³). *t*-statistics in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Coefficient scales follow the underlying data as constructed from WDI and MRIO sources (Table 1).

Our framework posits that manufacturing dependence, trade structure, income, and freshwater endowments shape countries' net virtual-water (NVW) positions. Table 4 summarizes the OLS results.

Income and development (H2). GDP per capita carries a negative and statistically significant coefficient in all three models. Given that NVW_i is defined as embodied-water exports minus imports, this finding implies that, conditional on trade and industrial structure, richer economies tend to exhibit smaller net NVW outflows (that is, relatively larger NVW inflows), consistent with upgrading toward less water-intensive export bundles at higher income levels.

Industrial composition (H1). Model 2 shows a strong negative association between manufacturing value added (% GDP) and NVW outflows. Higher manufacturing dependence correlates with larger NVW inflows, reflecting the import intensity of manufacturing supply chains (water embodied in intermediate inputs and in meeting urban/industrial demand).

Trade structure (H3–H4). Model 3 reinforces the central role of trade: exports are positively associated with NVW outflows, while imports are negatively associated—precisely the signs implied by the accounting mechanism. Export-oriented economies externalize water through commodity and intermediate trade; import-dependent economies draw on external water to meet domestic and export demand.

Endowments (H5). Renewable freshwater per capita is statistically insignificant across specifications, indicating that, conditional on trade and industrial structure, natural

endowments are not robust predictors of NVW net export status—consistent with **H5**'s implication that when water constraints are slack, greater endowments need not translate into higher net virtual-water outflows.

Controls. Resident consumption loads positively (a scale effect), and FDI is positive where included, consistent with the globalization of production networks. Taken together, the evidence supports **H1–H4** and is consistent with **H5**. The determinants highlight actionable levers—production efficiency, input substitution, and sourcing choices—over fixed endowments.

Table A.4 reports robustness checks. Models 7–9 winsorize continuous variables at the 1st/99th percentiles; coefficients retain their baseline signs and remain economically similar: GDP per capita is negative, resident consumption is positive, manufacturing share is negative, exports enter positively and imports negatively, while renewable freshwater per capita remains insignificant. Model 10 excludes observations from 2020 onward to abstract from the pandemic; results are again stable, with the key trade and structure variables preserving sign and significance. Overall, the determinants of NVW outflows are robust to outliers and to excluding the COVID-19 period.

5.3 Economic growth, development paths, and virtual water

Table 5 reports OLS models of real GDP growth on NVW flows and water endowments, adding controls sequentially from Models 4–6. These specifications are explicitly reduced-form and treat NVW as an observed outcome of trade and industrial structure rather than as an exogenous policy variable,⁴ so the coefficients are interpreted as conditional correlations rather than structural parameters.

Table 5 GDP growth rate and water resources

	Model 4	Model 5	Model 6
Virtual water net flow	0.0056 (0.097)	0.0083 (0.147)	0.0043 (0.077)
GDP per capita	2.317*** (5.884)	2.296*** (6.152)	2.063*** (5.070)
Resident final consumption expenditure	-0.886 (-1.300)	-0.862 (-1.303)	-1.950** (-2.127)
Renewable inland freshwater resources per capita	1.574***	1.470***	1.438***

⁴ Potential reverse causality (from growth to trade structure and NVW), omitted institutional or geographic factors, and measurement error in MRIO-based NVW measures mean that the coefficients in Table 5 should be interpreted as conditional correlations rather than structural parameters or causal effects.

	Model 4	Model 5	Model 6
	(3.057)	(2.928)	(2.813)
Net foreign direct investment		1.232 (0.220)	
Manufacturing value added (% GDP)		0.00542 (0.056)	
Exports of goods and services			4.013 (0.558)
Imports of goods and services			3.785 (0.446)
Constant	-2.342** (-2.334)	-2.257 (-1.527)	-2.484** (-2.401)
	<i>N</i>	1800	1649
	<i>R</i> ²	0.0233	0.0271
		0.0276	0.0276

Notes: *t*-statistics in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

In Model 4, the coefficient on NVW is small, positive, and statistically insignificant (0.0056 with a *t*-statistic of 0.097); the same pattern holds in Models 5–6. Because NVW is defined as outflows minus inflows, these estimates imply no systematic association between NVW inflows or outflows and short-run economic growth. Using the standard deviation of NVW (10.6 Bm³; Table 3), even the largest point estimate (0.0083 in Model 5) maps into an economic growth difference of well under 0.1 percentage points, which is economically negligible. In other words, countries that specialise in exporting or importing virtual water do not, on average, grow faster or slower than otherwise similar economies once trade structure, income, and other covariates are taken into account.

By contrast, renewable freshwater per capita enters with a positive and statistically significant coefficient in all three specifications, and GDP per capita is likewise positive and highly significant throughout. Resident final consumption expenditure is negatively related to economic growth and becomes statistically significant only in the most saturated specification (Model 6), while net foreign direct investment, manufacturing value added, and exports and imports of goods and services do not display robust effects in these reduced-form regressions. Overall *R*² values are modest, as is typical for annual cross-country economic growth regressions, and the estimates should be interpreted as correlations rather than strong causal claims.

From an ecological-economics perspective, these results play a reassuring, rather than central, role. They provide no evidence of a generic water resource curse: net virtual-water flows are essentially unrelated to short-run growth, and water-abundant economies—measured by renewable freshwater per capita—exhibit, if anything, slightly faster growth. Coupled with the flow regressions, which highlight trade structure and industrial composition over endowments, the economic growth results suggest that water-intensive development paths and green manufacturing strategies need not be at odds with macroeconomic performance, provided that embodied-water exposures are managed through efficiency improvements, input substitution, and resilient sourcing.

6. Discussion and conclusions

This study undertakes a global accounting of virtual water by combining a multi-region input–occupancy–output framework (Eora MRIO) with macroeconomic covariates from the WDI for 189 countries across the 2010–21 timeframe, and embeds this data in a tractable open-economy mechanism (Section 3). The framework delivers testable predictions for NVW positions and for the reduced-form relationship between embodied-water trade and economic growth, and the empirical evidence lines up closely with those predictions. The main results are robust to winsorization at the 1st/99th percentiles and to excluding post-2019 observations (Tables 4 and 5). Interpreted in ecological-economic terms, the central message is that *what* economies produce and trade—and *how* production is organized along global value chains—matters more than *how much* renewable freshwater they possess for explaining embodied-water balances and associated macro outcomes.

Descriptively, the global network of embodied-water trade is highly structured: advanced economies typically occupy net-export positions, while many developing economies appear as net importers. Translating MRIO flows into country-year NVW measures and merging them with macro variables, we find that scale effects, trade volumes, and industrial composition explain most of the cross-country variation in net positions (Table 4). Across specifications, resident final consumption expenditure is strongly and positively associated with NVW outflows, while GDP per capita enters with a negative and statistically significant coefficient, indicating that, for a given level of consumption, richer economies tend to exhibit smaller net NVW outflows. Trade and production structure matter as well: higher export volumes are associated with larger NVW outflows, whereas a higher manufacturing value-added share and greater import volumes are associated with larger NVW inflows. By contrast, renewable inland freshwater resources per capita are not a robust predictor of net-export status once demand and trade-related variables are controlled. These patterns echo the analytical logic of our framework: when the water constraint is slack, endowment levels do not mechanically determine embodied-

water balances—what matters is production technology, supply-chain configuration, and the composition of final demand.

From an ecological-economics perspective, these findings provide new global stylised facts on how economic structure governs the redistribution of freshwater use through trade. They show that NVW is better understood as an outcome of specialisation and trade costs than as a simple reflection of hydrological abundance, and that virtual-water trade can either exacerbate or alleviate local scarcity depending on where water-intensive stages of production are located. For policy and management, the results translate into concrete levers. For countries that are net *exporters* of embodied water, priorities include reducing the water intensity of export supply chains through process efficiency improvements, reuse and recirculation, leakage control, and adoption of best-available technologies in water-intensive sectors. For net *importers*, the emphasis shifts toward sourcing and procurement: diversifying origins of water-intensive imports across basins and seasons, incorporating embodied-water metrics and source-basin stress into public procurement and corporate supplier selection, and stress-testing critical trade corridors against droughts, heat waves, and policy shocks. Disclosure and footprinting standards (e.g., ISO 14046) can improve comparability, align firm-level incentives with local scarcity, and support more transparent governance of shared water resources.

The economic growth regressions play a complementary role. They ask whether water abundance—measured either by renewable freshwater endowments or by net virtual-water flows—is associated with weaker performance in the spirit of a “water resource curse.” The answer, in our aggregate data, is no. Net virtual-water flows are essentially unrelated to short-run GDP growth, and water-abundant economies, if anything, grow slightly faster. While GDP growth is only one dimension of development, this finding suggests that water-intensive development paths and green industrialisation strategies are not inherently self-defeating from a macroeconomic perspective. Instead, the main risks lie in unmanaged local scarcity, exposure to hydrological shocks, and unequal distribution of benefits and burdens along supply chains—all of which can be addressed by policies that change the *structure* of production and trade rather than the endowments themselves.

Several limitations qualify our conclusions and point to directions for future research. First, the econometric analysis is explicitly reduced-form and not designed for causal identification; potential endogeneity between economic growth, trade structure, and industrial composition remains a concern, as does measurement error in MRIO flows arising from sectoral aggregation, database balancing, and the imputation of missing environmental satellite data. Second, our baseline aggregates blue, green, and grey water and does not distinguish withdrawals from depletion or track groundwater sustainability, so ecological risks at finer spatial scales may be understated. Third, NVW is constructed at the national level and cannot reveal within-country distributional impacts or binding

constraints at particular basins, seasons, or communities, where management decisions are often taken. Addressing these issues would enhance both the ecological-economic interpretation and the usefulness of NVW metrics for policy.

Several extensions follow naturally. On the econometric side, future work could exploit structural-gravity approaches or Bartik-type instruments, together with hydro-climatic variations, to identify causal effects of exports, imports, and manufacturing dependence on NVW and economic growth. Linking firm-level customs and production records to sub-national water accounts would help open the “black box” of supply chains and quantify the imported-intermediate channel more directly, including distributional and justice dimensions. On the accounting side, triangulating across MRIO databases (e.g., Eora, EXIOBASE, WIOD) and explicitly propagating measurement uncertainty could provide a tighter basis for policy targeting. Finally, disaggregating blue/green/grey components and integrating water-quality metrics and climate extremes into dynamic, uncertainty-aware scenarios would bring NVW analysis closer to sustainability thresholds and to the time horizons relevant for both regulators and long-lived private investments.

In summary, the global pattern we document is economic rather than endowment-driven: embodied-water balances are shaped primarily by specialisation, trade volumes, and value-chain position. Our results support the mechanism’s predictions for how trade structure and industrial composition shape NVW positions, are consistent with the view that renewable freshwater endowments do not robustly predict net-export status when water constraints are slack, and show no evidence of a macro-level water resource curse. Water-intensive development paths can coexist with robust economic performance when production and trade shift toward lower water intensity and when embodied-water exposures are actively managed through efficiency upgrades, input substitution, diversified sourcing, and governance that aligns use with local scarcity, ecological limits, and broader goals of sustainable and equitable development.

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Appendix

Table A.1 Countries/regions with WDI coverage (185) (continued).

Aruba	Afghanistan	Angola	Albania
Andorra	United Arab Emirates	Argentina	Armenia
Antigua and Barbuda	Australia	Austria	Azerbaijan
Burundi	Belgium	Benin	Burkina Faso
Bangladesh	Bulgaria	Bahrain	Bahamas, The
Bosnia and Herzegovina	Belarus	Belize	Bermuda
Bolivia	Brazil	Barbados	Brunei Darussalam
Bhutan	Botswana	Central African Republic	Canada
Switzerland	Chile	China	Cote d'Ivoire
Cameroon	Congo, Dem. Rep.	Congo, Rep.	Colombia
Cabo Verde	Costa Rica	Cuba	Cayman Islands
Cyprus	Czechia	Germany	Djibouti
Denmark	Dominican Republic	Algeria	Ecuador
Egypt, Arab Rep.	Eritrea	Spain	Estonia
Ethiopia	Finland	Fiji	France
Gabon	United Kingdom	Georgia	Ghana
Guinea	Gambia, The	Greece	Greenland
Guatemala	Guyana	Hong Kong SAR, China	Honduras
Croatia	Haiti	Hungary	Indonesia
India	Ireland	Iran, Islamic Rep.	Iraq
Iceland	Israel	Italy	Jamaica
Jordan	Japan	Kazakhstan	Kenya
Kyrgyz Republic	Cambodia	Korea, Rep.	Kuwait
Lao PDR	Lebanon	Liberia	Libya
Liechtenstein	Sri Lanka	Lesotho	Lithuania

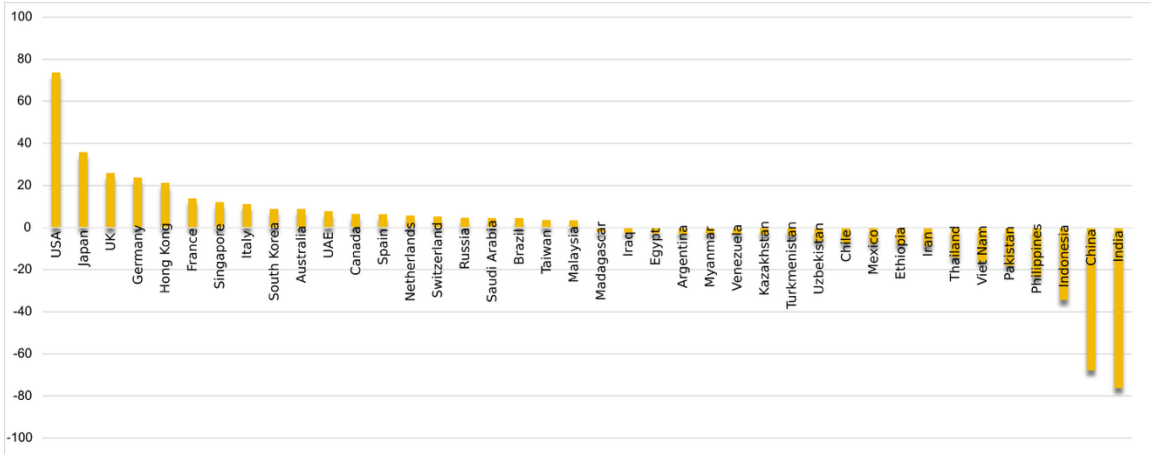
Table A.1 Countries/regions with WDI coverage (185) (continued).

Luxembourg	Latvia	Macao SAR, China	Monaco
Moldova	Madagascar	Maldives	Mexico
North Macedonia	Mali	Malta	Myanmar
Montenegro	Mongolia	Mozambique	Mauritania
Mauritius	Malawi	Malaysia	Namibia
New Caledonia	Niger	Nigeria	Nicaragua
Netherlands	Norway	Nepal	New Zealand
Oman	Pakistan	Panama	Peru
Philippines	Papua New Guinea	Poland	Korea, Dem. People's Rep.
Portugal	Paraguay	West Bank and Gaza	French Polynesia
Qatar	Romania	Russian Federation	Rwanda
Saudi Arabia	Sudan	Senegal	Singapore
Sierra Leone	El Salvador	San Marino	Somalia
Serbia	South Sudan	Sao Tome and Principe	Suriname
Slovak Republic	Slovenia	Sweden	Eswatini
Seychelles	Syrian Arab Republic	Chad	Togo
Thailand	Tajikistan	Turkmenistan	Trinidad and Tobago
Tunisia	Turkiye	Tanzania	Uganda
Ukraine	Uruguay	United States	Uzbekistan
Venezuela, RB	British Virgin Islands	Viet Nam	Vanuatu
Samoa	Yemen, Rep.	South Africa	Zambia
Zimbabwe			

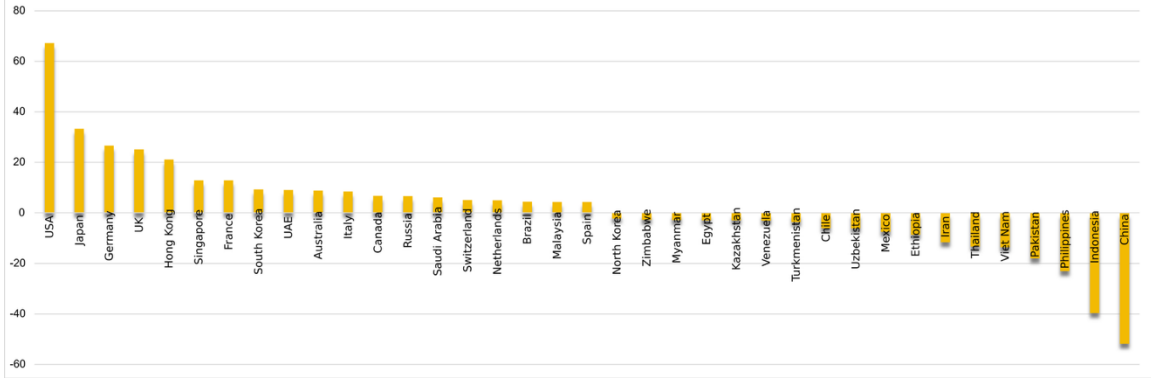
Table A.2 Net virtual-water flow ranking (Bm^3)

Top 20 net exporters			Top 20 net importers		
Rank	Country (ISO3)	Net flow	Rank	Country (ISO3)	Net flow
1	USA	60.6621	1	IND	-78.5295
2	JPN	36.4426	2	CHN	-43.5838
3	GBR	24.3547	3	STP	-34.3587
4	DEU	21.1511	4	PHL	-20.7181
5	HKG	20.4263	5	IDN	-16.2158
6	FRA	12.7706	6	PAK	-16.1609
7	KOR	10.8497	7	VNM	-12.1574
8	SRB	10.3833	8	THA	-11.7662
9	AUS	10.0863	9	IRN	-10.5730
10	RUS	9.1714	10	SGP	-10.0744
11	ARE	8.7073	11	BRN	-9.0641
12	CAN	7.0439	12	ETH	-6.9423
13	CHE	6.6914	13	MEX	-6.2020
14	NLD	5.9603	14	CYM	-5.6083
15	SAU	5.4042	15	CHL	-5.5926
16	ESP	5.3882	16	UZB	-5.2551
17	BRA	5.1908	17	VGB	-4.9046
18	POL	4.5578	18	ZWE	-3.2298
19	MYS	4.2683	19	SMR	-2.8403
20	ITA	4.1494	20	IRQ	-2.7773

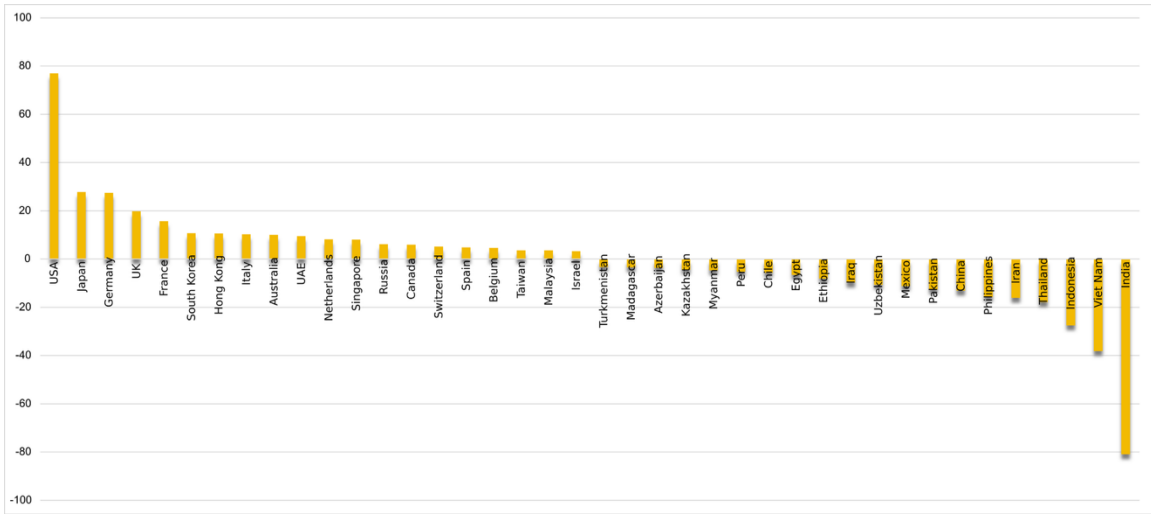
Notes: Bm^3 = billion cubic meters. Positive values denote net exporters (outflows > inflows); negative values denote net importers. Country identifiers follow ISO 3166-1 alpha-3 codes. Values rounded to 4 decimal places.



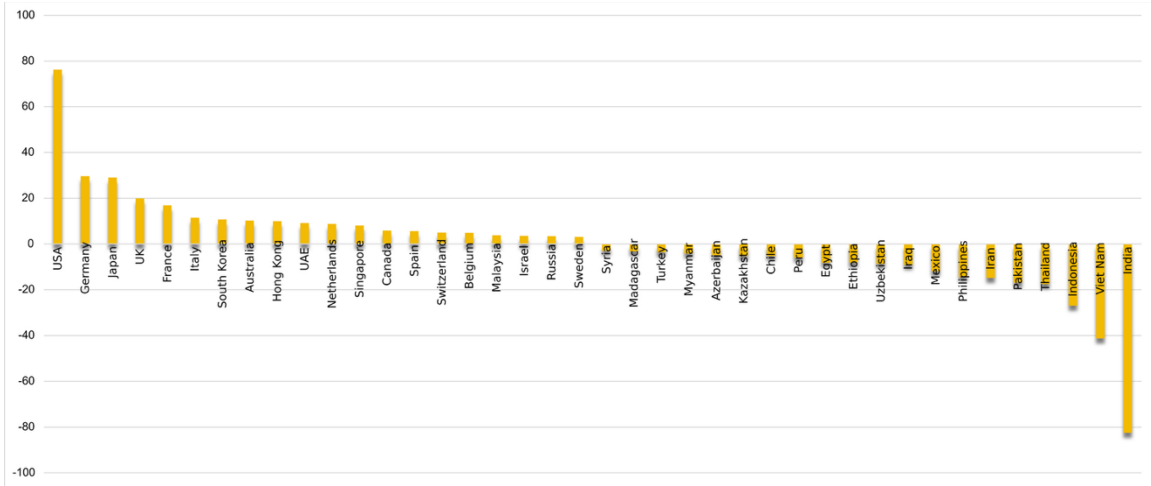
(i) 2010



(ii) 2013



(iii) 2017



(iv) 2021

Figure A3: Total NW flow ranking by country. For each year, the histograms show the 20 countries with the largest net outflows and the 20 countries with the largest net inflows.

Table A.3 Top 20 virtual-water outflows and inflows (Bm³)

Top 20 outflows			Top 20 inflows		
Rank	Country (ISO3)	Outflow	Rank	Country (ISO3)	Inflow
1	USA	98.2437	1	CHN	96.2422
2	CHN	52.6584	2	IND	90.1018
3	JPN	47.6000	3	USA	37.5817
4	DEU	33.3814	4	STP	34.3987
5	GBR	25.4613	5	IDN	24.7478
6	HKG	20.5191	6	PHL	24.3430
7	FRA	19.7836	7	SGP	21.9377
8	KOR	19.4351	8	THA	20.7077
9	RUS	18.5274	9	PAK	17.2202
10	CAN	16.8368	10	VNM	16.5348
11	ITA	16.7447	11	MEX	15.6331
12	ESP	13.2283	12	IRN	15.0616
13	AUS	12.8426	13	ITA	12.5953
14	SGP	11.8632	14	DEU	12.2303
15	IND	11.5723	15	JPN	11.1573
16	NLD	10.7717	16	CAN	9.7929
17	BRA	10.4569	17	RUS	9.3560
18	SRB	10.3840	18	BRN	9.3172
19	MEX	9.4312	19	KOR	8.5854
20	ARE	9.1528	20	CHL	8.1953

Notes: Bm³ = billion cubic meters. Country identifiers follow ISO 3166-1 alpha-3 codes. Values rounded to 4 decimal places.

To assess the sensitivity of our findings, we implement two complementary strategies. First, we winsorize all continuous variables at the 1st and 99th percentiles to limit the influence of outliers. Second, to mitigate potential distortions from the COVID-19 period, we re-estimate the models on the pre-2020 sample (i.e., dropping observations with year ≥ 2020).

Table A.4 reports the virtual-water regressions under these checks: Models 7-9 apply winsorization, and Model 10 restricts the sample to the pre-2020 period. Table A.5 repeats the exercise for the GDP–water specifications: Models 11-13 are winsorized, and

Model 14 uses the pre-2020 sample. Across these variants, the qualitative conclusions are unchanged relative to the baseline results.

Table A.4 Robustness checks for Table 4

	Model 7	Model 8	Model 9	Model 10
GDP per capita	- 0.381*** (-2.586)	-0.278* (-1.835)	- 0.629*** (-3.899)	- 0.611*** (-3.112)
Resident final consumption expenditure	4.107*** (19.718)	4.172*** (19.465)	3.921*** (11.778)	8.145*** (26.667)
Renewable inland freshwater resources per capita	0.0122 (0.063)	0.137 (0.671)	-0.0572 (-0.281)	-0.0632 (-0.218)
Net foreign direct investment		16.81*** (7.628)		- 0.611*** (-3.112)
Manufacturing value added (% GDP)		- 0.224*** (-5.743)		
Exports of goods and services			11.44*** (4.015)	
Imports of goods and services			- 8.916*** (-2.644)	
Constant	- 1.070*** (-2.858)	1.329** (2.218)	-0.935** (-2.275)	- 2.115*** (-3.878)
<i>N</i>	1801	1650	1699	1504
<i>R</i> ²	0.193	0.243	0.204	0.348

Notes: The dependent variable is NVW outflow, measured in billion cubic meters (Bm³). *t*-statistics are reported in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Coefficients are reported in the original units of the underlying variables constructed from WDI and MRIO sources (see Table 1).

Table A.5 Robust test for Table 5

	Model 11	Model 12	Model 13	Model 14
Virtual water net flow	0.00184 (0.042)	0.00670 (0.151)	0.00159 (0.036)	0.00481 (0.083)
GDP per capita	2.033*** (6.695)	1.993*** (6.760)	1.807*** (5.668)	1.481*** (3.521)
Resident final consumption expenditure	-0.770 (-1.465)	-0.743 (-1.424)	- (-2.714)	-0.908 (-1.127)
Renewable inland freshwater resources per capita	1.523*** (3.837)	1.381*** (3.485)	1.377*** (3.435)	1.104* (1.789)
Net foreign direct investment		0.0338 (0.443)		
Manufacturing value added (% GDP)		1.118 (0.252)		
Exports of goods and services			0.791 (0.140)	
Imports of goods and services				7.381 (1.111)
Constant	-1.874** (-2.423)	-2.086* (-1.787)	-2.074** (-2.557)	0.0198 (0.017)
	<i>N</i>	1800	1649	1698
	<i>R</i> ²	0.0310	0.0339	0.0356
				1503
				0.0102

Notes: *t*-statistics are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. All other definitions, units, and data sources are as in Table 1.