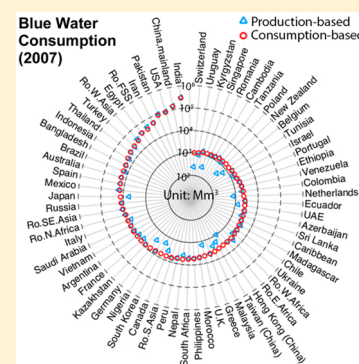


Hybrid Analysis of Blue Water Consumption and Water Scarcity Implications at the Global, National, and Basin Levels in an Increasingly Globalized World

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Supporting Information

ABSTRACT: As the fifth global water footprint assessment, this study enhanced previous estimates of national blue water consumption (including fresh surface and groundwater) and main economic activities with (1) improved spatial and sectoral resolution and (2) quantified the impacts of virtual water trade on water use and water stress at both the national and basin level. In 2007, 1194 Gm³ of blue water was consumed globally for human purposes. The *consuming (producing)* of primary and manufactured goods and services from the sectors of “Primary Crops and Livestock”, “Primary Energy and Minerals”, “Processed Food and Beverages”, “Non-food Manufactured Products”, “Electricity”, “Commercial and Public Services”, and “Households” accounted for 33% (91%), ~ 0% (1%), 37% (<1%), 13% (1%), 1% (2%), 15% (3%), and 2% (2%) of the world’s total blue water consumption, respectively. The considerable differences in sectoral water consumption accounted for by the two perspectives (*consumption- vs production-based*) highlight the significance of the water consumed indirectly, upstream in the supply chain (i.e., > 70% of total blue water consumption) while offering additional insights into the water implications of critical interconnected economic activities, such as the water-energy nexus. With 145 Gm³ (12%) of the blue water consumption embedded in the goods and services traded internationally, 89 countries analyzed were net blue water importers at the national level. On the basin level, the impacts of virtual water trade on water stress were statistically significant for basins across the world and within 104 countries; virtual water trade mitigated water stress for the basins within 85 of the 104 countries, including all of those where there are moderate and greater water stress countrywide (except Italy).



INTRODUCTION

Global water demand grew twice as fast as the world’s population over the past few decades.¹ According to the latest projection, global water demand will increase by 55% from 2000 to 2050.² Meanwhile, due to the growing sectoral specialization and globalization of the world economy, local consumption of various goods and services is increasingly impacting distant local hydrological cycles.^{3,4} As such, there are greater concerns over local, regional, and global water use and stress that will degrade water quality and ecosystem health and directly limit human and economic development, such as energy generation and agricultural production, threatening human well-being and escalating regional conflicts.^{5–10}

As illustrated by Figure 1, existing water use statistics are based on direct water usage by the main water users (e.g., agriculture, industries, and households) within a nation’s territory¹¹ (a.k.a. production-based water use accounts) and have led to the conventional water management and policies that are (1) limited to domestic water resources, and (2) allocate water use and its impacts to the direct water users (e.g., farmers, manufacturers, and homeowners). The emerging consumption-based water use metric, water footprint (WF), traces both direct and indirect water consumption (i.e., water consumed to produce materials, energy, labor, and the rest of nonwater inputs) throughout the

full supply chain of finished goods and services to their final consumers (as opposed to the intermediate demand of firms for raw materials or unfinished goods).^{12–14} In this way, WF highlights the final consumers’ purchasing and consuming of finished goods and services as the ultimate driving forces of the water inputs and impacts along the numerous upstream production processes. Within the consumption-based water use accounts, the water used to produce commodities that are traded from one place to another are known as “virtual water”, which further reveals how water resources in one region are used to support consumption of goods and services in another. As such, virtual water has been suggested as a strategic solution to alleviate regional water deficits if water-scarce regions import water-intensive commodities from water-abundant regions instead of producing them locally.^{15–19} Given the growing supply chains, the increasing role of international trade, and the trends of outsourcing polluting industries to regions with less restrictive environmental regulations,^{4,20} the consumption-based water use accounts have become particularly critical for the

Received: February 2, 2016

Revised: April 21, 2016

Accepted: April 21, 2016

Published: April 21, 2016

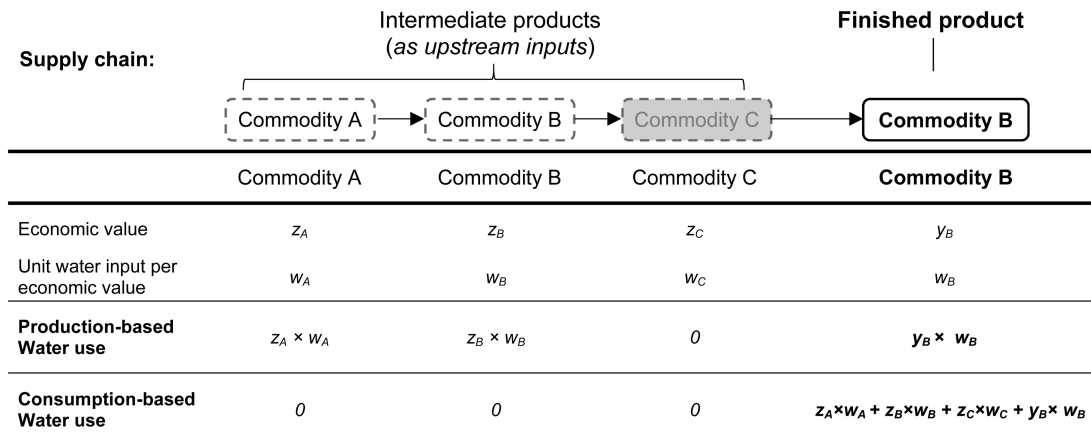


Figure 1. An illustration of the production- and consumption-based water use accounting. On top of the figure is a simplified multiregional supply chain. It contains three upstream sectors producing Commodities A, B, and C as intermediate products, which ultimately lead to the production of Commodity B as a finished product and consumed by final consumers in country *r*. As the figure illustrates, the production of one commodity (e.g., Commodity B as electricity or automobiles) typically needs the same group of commodity as an input. Some intermediate products used upstream the supply chain are produced outside of the country where the finished products are consumed, as illustrated here by Commodity C. Water consumption of Commodity C is thus not accounted in country *r*'s production-based water use.

planning and assessment of water resources, and food security management.¹⁸

Considered a comprehensive yet still evolving measure of the anthropogenic impacts on hydrologic systems, WFs have been assessed and improved at global, national, and subnational scale by a number of studies over the past two decades, for example, refs 3,4,18,16, and 21–25. In particular, recent studies quantified fully the direct and partially the indirect water requirements of hundreds of crop (and crop-derived) products as well as animal products at a subnational scale^{21,22} and highlighted the significant water requirements and conservation potential associated with consumer diets.^{18,26,27} The increasing importance of global virtual water trade was revealed by the global displacements of the EU's WFs,⁴ the impacts of the top virtual water users (i.e., countries and industries) on domestic and foreign water use in the context of water scarcity,^{3,18} and increased trade connections and water savings associated with the global food trade during the past two decades.²⁰ For over 400 river basins worldwide, the environmental sustainability of human water uses were assessed and the most critical water management needs were pinpointed based on the monthly variability in water consumption and availability due to human consumption and climate patterns, respectively.^{28–30}

Two main approaches: the process-based (i.e., bottom-up) and input-output (I/O) table-based (i.e., top-down) were used by existing studies. Briefly, the process-based approach estimates WFs using detailed product- or process-level data (e.g., the WFs of U.S.-produced beef are calculated from the water used for cattle drinking, washing and cleaning, and growing and mixing the feed under various production systems in the U.S., and the amount of beef consumed domestically and traded to other countries^{12,22}). Calculating WFs with such significant details, especially for individual agricultural products, the production-based approaches, however, are unlikely to capture every process and sector along growing supply chains for all goods and services provided by the global economic system. Therefore, process-based WFs cannot robustly distinguish the final users from intermediate users of products, and subsequently the water embedded.^{31,32} The top-down approach is based on the I/O tables that inventory monetary transactions between aggregated sectors for an entire regional or national economy; thus, the

I/O-based analysis can capture and identify the intermediate and the final consumption of commodities and the water flows within a comprehensive economic system.³³ The most recent development, the environmentally extended multiregional input-output (MRIO) models, estimate WFs based on the global economic transactions of goods and services, further distinguishing between the water consumed domestically and abroad, and accounting for the region-specific production structures, technologies, and efficiencies.^{3,13,32,34} In comparison to the process-based approach, every generalized I/O analysis, especially the environmental MRIO analyses, have much lower sectoral resolution as various subsectors are aggregated into the same sector in the I/O tables.^{3,13} More importantly, the two approaches result in WF estimates of significant discrepancies,³² (see Supporting Information Table S1), creating reasonable skepticism in the robustness and thus policy relevance of WF accounting. As such, a hybrid approach that enriches the multiregional input-output (MRIO) approach with detailed data of agricultural products has been suggested as a methodological improvement for water footprinting.^{32,35} This hybrid approach was developed³⁶ and recently attempted in a European-only study.⁴

This study is the fifth assessment of global WF, after Hoekstra & Hung,¹⁶ Hoekstra & Chapagain,²⁴ Fader et al.,²⁵ and Hoekstra & Mekonnen.¹⁸ Uniquely, the objectives of this analysis are 2-fold: (1) to enhance the global estimates of consumptive uses of fresh surface and groundwater (a.k.a. blue water) associated with the nations' producing and consuming of all economic goods and services (i.e., production- vs consumption-based accounts), re-evaluating the roles of the nations and economic sectors from the two perspectives, and (2) to assess the impacts of virtual water trade on freshwater availability and stress at various spatial scales. This study improves upon earlier WF studies in a number of respects. First, the results and analyses were based on a hybrid WF accounting model with improved spatial and sectoral resolution. Based on MRIO data of 134 world countries/regions and 57 sectors covering the entire global economy in 2007, the hybrid model integrates detailed production, trade, and water requirement estimates of 209 primary crop products. In comparison, existing IO- and process-based WF studies with a global scope were based on an earlier time frame and lower sectoral and regional

disaggregation, for example, refs 3,18, and 37, whereas the prior hybrid model integrated fewer crop products and was applied to the EU member states only.⁴ The improved hybrid model also distinguishes the direct water withdrawal rates ($\text{m}^3/\$$) and consumption coefficients for each of the 57 economic sectors in each country/region based on the best information available and justifiable assumptions. The enhanced characterization of water consumption rates can better capture the water consumption associated with not only primary agricultural products that were the focus of previous WF studies (e.g., refs 18 and 25), but also primary energy and materials, manufactured products and commercial services, resulting in a global blue WF (WF_b) assessments for 57 economic sectors covering the entire global economic system. This was not possible in previous studies where a homogeneous direct water usage rate (i.e., the same m^3 of water withdrawal per \$ spent) was assumed for a variety of economic sectors within the main category of “industrial” or “commercial”. Second, this study was among the first efforts that assessed the impact of international virtual water trade on water use and scarcity at the global, national, and basin level. Based on the hybrid model, the transboundary virtual water accounted for here considers not only agricultural products, as was initially defined³⁸ and often assessed,^{16,20,39} but also considers various industrial and commercial goods and services, realizing a more comprehensive assessment of international virtual water trade. Lastly, the additional nuance provided by examining the methodological uncertainties of WF_b estimates highlight current limitations and future research needs of WF accounting. The examination suggests improved transparency as well as spatial- and sector-disaggregation in global and national water footprinting can better inform decision-making in terms of impacts, reliance, and leverage on water appropriations domestically as well as internationally for industrial and government actors.

MATERIALS AND METHODS

Hybrid WF Accounting Model. The analysis was carried out using an improved hybrid WF accounting approach that was built upon the methodologies described in published literature (i.e., refs 4,13, and 36), combining the advantages of the state-of-the-art MRIO model and process-based approaches. Economic input-output data by 57 sectors for 134 regions in 2007 was retrieved from the GTAP 8 database,⁴⁰ which was the most recent GTAP (Global Trade Analysis Project) release during the time this analysis was performed. Despite some shortcomings, the GTAP database is considered one of the most detailed and reliable data sets for MRIO analysis^{13,41} and was used by several widely cited studies, for example, refs 4, 14, and 42. A higher level of sectoral resolution was achieved in the improved hybrid model by enriching the sectors originally included in the GTAP MRIO database with detailed process-based information. Specifically, 8 out of the 57 MRIO sectors that represent primary crop commodity aggregates were detailed with production and trade data of 209 individual primary crop products and feed information in the FAO Food Balance Sheets, obtained from FAOSTAT.⁴³

The environmental extension matrix inventorying unit sectoral water uses was built using water withdrawal data of 177 countries collected from AQUASTAT country database,¹¹ Australian Bureau of Statistics,⁴⁴ U.S. Geological Survey,⁴⁵ and Statistics Canada,⁴⁶ by-sector water consumption coefficients estimated from refs 45–50 (see Supporting Information Table S2), and unit blue water requirements (in m^3/ton) of the 209 primary

crop products obtained from ref 21. Further, unit water use rates for each of the 49 nonprimary-crop GTAP sectors was calculated based on the relative water intensity information among those sectors⁵¹ (the method is detailed in the Supporting Information). Consistent with refs 13 and 52 no WF_b (i.e., irrigation) was assumed for primary forestry and wood products, that is, GTAP Sector 13. Water withdrawn for aquaculture was assumed to be completely returned to the environment after use⁵³ but a recent study cautions that the replacement of fish meal and fish oil with terrestrial feed ingredients as a potential way of relieving fisheries' pressure to provide feed may result in considerable increases of freshwater consumption.⁵⁴

Data from different sources were integrated through careful sector matching using the product concordances among GTAP, FCL (FAOSTAT Commodity List), and HS (Harmonized System) 2007.^{55,56} For countries with missing information, data of adjacent regions or world average values were used. Acknowledging that, for several parameters used in the hybrid model, there is a lack of updated and accurate information compatible with the spatial coverage of this analysis, we conducted sensitivity analysis to investigate the robustness of the model and the main findings. The sensitivity analysis was illustrated by varying the water consumption coefficients of thermoelectricity generation (Cf_{te}) by $\pm 50\%$. Specifically, the model was simulated by (1) changing one country's Cf_{te} by -50% and $+50\%$, respectively, while keeping the coefficients constant for the other countries, and 2) changing all countries' Cf_{te} simultaneously by -50% and $+50\%$, respectively. As such, results from the sensitivity analysis reflect an extensive range of possible variations. The whole model was written in Matlab. Detailed descriptions of the model are included in the Supporting Information.

Impacts of Virtual Water Trade on Basin-level Water Stress. Anthropogenic water use, that is, *water withdrawal* (water removed from a ground- or surface water source for human use) and *water consumption* (the part of water withdrawal that is evaporated, transpired by plants, incorporated into products or crops, or otherwise removed from the immediate water environment), is one of the mostly used metrics of changes in water quality and human impacts on water environments.⁵⁰ Reductions in freshwater withdrawal and consumption will not only reduce the need to take water out of local rivers and aquifers and permit new demands without expanding the capacity of existing infrastructures, but also can improve water quality and increase environmental values in- and downstream, providing enhanced recreation, fishing, tourism, and other benefits.⁵⁷

The absolute measures of water use, if evaluated in the context of water availability, can indicate how close a region may be to water scarcity and degradation and thus identify the hotspots for water management and investment.^{57,58} However, there is no consensus approach to integrate the estimates of WFs with the knowledge of water scarcity. Several studies scaled water flows using the country-level “water use to availability” (*w.t.a.*) ratio of the originating country to distinguish the effects of additional water withdrawals on stressed and nonstressed waters. It was shown that this weighting could significantly alter the environmental impact assessed for product ingredients^{58,59} and the net virtual water trade balance estimated for a country/region.³ In a recent study, the impacts of physical and virtual water transfers on regional water stress alleviation within China were assessed using the metrics of actual and hypothetical water stress index, which were calculated as the ratio of a province's total annual water withdrawals to its available water resources with and without importing water from other provinces, respectively.⁶⁰

Here, to investigate the water stress implications of human water uses and the increasingly intense virtual water trade at the basin level, water stresses with and without global trade were assessed for basins worldwide. Developed from the actual and hypothetical water stress indices proposed in,⁶⁰ the water stress index of basin i with and without international trade (WSI_i^{BAU} and WSI_i^{NT} ; BAU = business as usual; NT = “No Trade”) were calculated as the w.t.a. ratio of the water withdrawal from basin i with and without international trade (WW_i^{BAU} and WW_i^{NT}) to basin i 's mean annual blue water availability (BA_i), respectively (eq 1 and eq 2):

$$WSI_i^{BAU} = \frac{WW_i^{BAU}}{BA_i} \quad (1)$$

$$WSI_i^{NT} = \frac{WW_i^{NT}}{BA_i} \quad (2)$$

As such, the differences between the two water stress indices represent the effects of international virtual water trade in terms of increasing (i.e., $WSI_i^{BAU} > WSI_i^{NT}$) or mitigating (i.e., $WSI_i^{BAU} < WSI_i^{NT}$) the water stress within basin i . At the basin scale, water withdrawal and availability in 2007 were estimated based on the basin delineations and basin-level information on >25 000 basins derived from ref 61. After excluding basins that are arid or where the water withdrawals are low (i.e., available blue water and water withdrawal less than 0.03 and 0.012 m³/m², respectively) over 12 000 basins accounting for 72% of the total areas were included in this analysis. More specifically:

- (1) WW_i^{BAU} was calculated by distributing the production-based national water withdrawals in 2007 to basins within the countries/regions according to the basin-level water withdrawal estimates for the year 2010,⁶¹ assuming minimal changes of the relative water withdrawals among basins within each country/region between 2007 and 2010;
- (2) Instead of using the consumption-based national water withdrawals to represent the countries/regions' water withdrawals under the “No Trade” scenario, as was done in,⁶⁰ WW_i^{NT} was estimated using each country/region's input-output structure, water use efficiencies, and crop water requirements to reflect that goods and services consumed by each country/region would be produced based on domestic economic structure, technological efficiencies, and physical characteristics. Without these adjustments, the hypothetical water withdrawals and water stress would be overestimated for countries where the domestic supply chains have higher water efficiencies than the global supply chains, and vice versa;
- (3) At the basin level, WW_i^{NT} was calculated assuming additional increases or reductions of a country/region's water withdrawals without international trade (i.e., $WW_i^{NT} - WW_i^{BAU}$) would be distributed among all basins within its territory, proportional to the magnitudes of current basin-level water withdrawal (i.e., WW_i^{BAU}), given they reflect the availability of infrastructure necessary for withdrawing water (e.g., public water treatment facilities, farms equipped with irrigation systems, power plants, and factories running on self-supplied waters);
- (4) The mean annual blue availability in basin i during 1950–2008 (BA_i) was obtained from ref 61;
- (5) While using the w.t.a. ratio, moderate, severe, and extreme water stresses are typically defined as when the annual withdrawals exceed 20%, 40%, and 100% of the water resources available, respectively.^{5,60,62}

RESULTS

As there are mixed use of terminologies in existing studies, throughout this analysis, the accounting of consumption-based blue water (i.e., WF_b) is defined as the consumptive freshwater usage withdrawn from surface- and ground- sources throughout an entire supply chain, possibly across multiple countries/regions, and assigned to the final end users of the finished products. Further, the production-based blue water consumption (PWC_b) is the consumptive freshwater withdrawn from surface- and ground- sources for production within a nation's territory and is assigned to the direct water users (e.g., farmers, industries, and households). Among the 134 global countries/regions included in the GTAP 8 database and analyzed here, 115 are individual sovereignties and 19 are composite regions (referred to as “Rest of...”) accounting for the rest of the economies in the world. The analyses here focused on the individual sovereignties. “n.e.c.” means “not elsewhere classified” as used in sectoral classifications. Detailed descriptions and classifications of the regions/countries and sectors, and results for all 134 regions/countries are available in the [Supporting Information](#).

The WF_b and PWC_b of Nations. In 2007, 1194 Gm³ of blue water was consumed (3,990 Gm³ withdrawn) for human purposes by the 134 regions/countries. The global blue water consumption, as shown by [Figure 2](#), was largely attributable to the production and consumption of goods and services in a few countries. Based on the consumption-based accounts (i.e., WF_b), 799 Gm³/year or 67% of the world's total freshwater consumption was ultimately driven by the demand and consumption of finished goods and services in ten countries, including (in Gm³/year) India (~301), mainland China (~137), the United States of America (~95), Pakistan (~88), Iran (~54), Egypt (~40), Turkey (~25), Thailand (~22), Indonesia (~20), and Bangladesh (~17), where 54% of the world's population resided in 2007. In contrast, WF_b s of the bottom 100 countries, or 30% of the world's population, accounted for 18% of the world's total WF_b . Over half of the top 10 countries are located in Asia, whereas African and EU countries dominate the bottom 100 countries ([Supporting Information Figure S2](#)). The rankings of the top countries were similar when the production-based accounts (i.e., PWC_b) were used ([Figure 2](#)). 70% or 839 Gm³ of the blue water flows consumed globally originated from ten countries, each of which contributed 17 (Australia) to 314 (India) Gm³/year supporting consumers worldwide. India (314 Gm³/year), mainland China (150 Gm³/year), and the United States (101 Gm³/year) had the largest PWC_b s, that is, over 48% of the world's blue water consumption originated from one of these three countries that collectively occupies only 14% of the world's land area. Only 13% or 155 Gm³ blue water was consumed within the 100 countries having the lowest PWC_b s.

The volumetric differences between WF_b and PWC_b , also known as a nation's net virtual water import, are highlighted by the red shadings in [Figure 2](#). Although the top eight nations perfectly overlapped, the two accounting perspectives resulted in different rankings and water volumes assigned to most countries. Beyond the volume totals, the sectoral composition of PWC_b and WF_b were also discrepant. Based on the production-based accounts, it has been established that agricultural practices, and irrigation in particular, significantly dominates human water appropriations globally and within most countries.¹ The PWC_b results here suggest that 89% or 1068 Gm³ blue water was consumed (68% or 2730 Gm³ withdrawn) directly irrigating

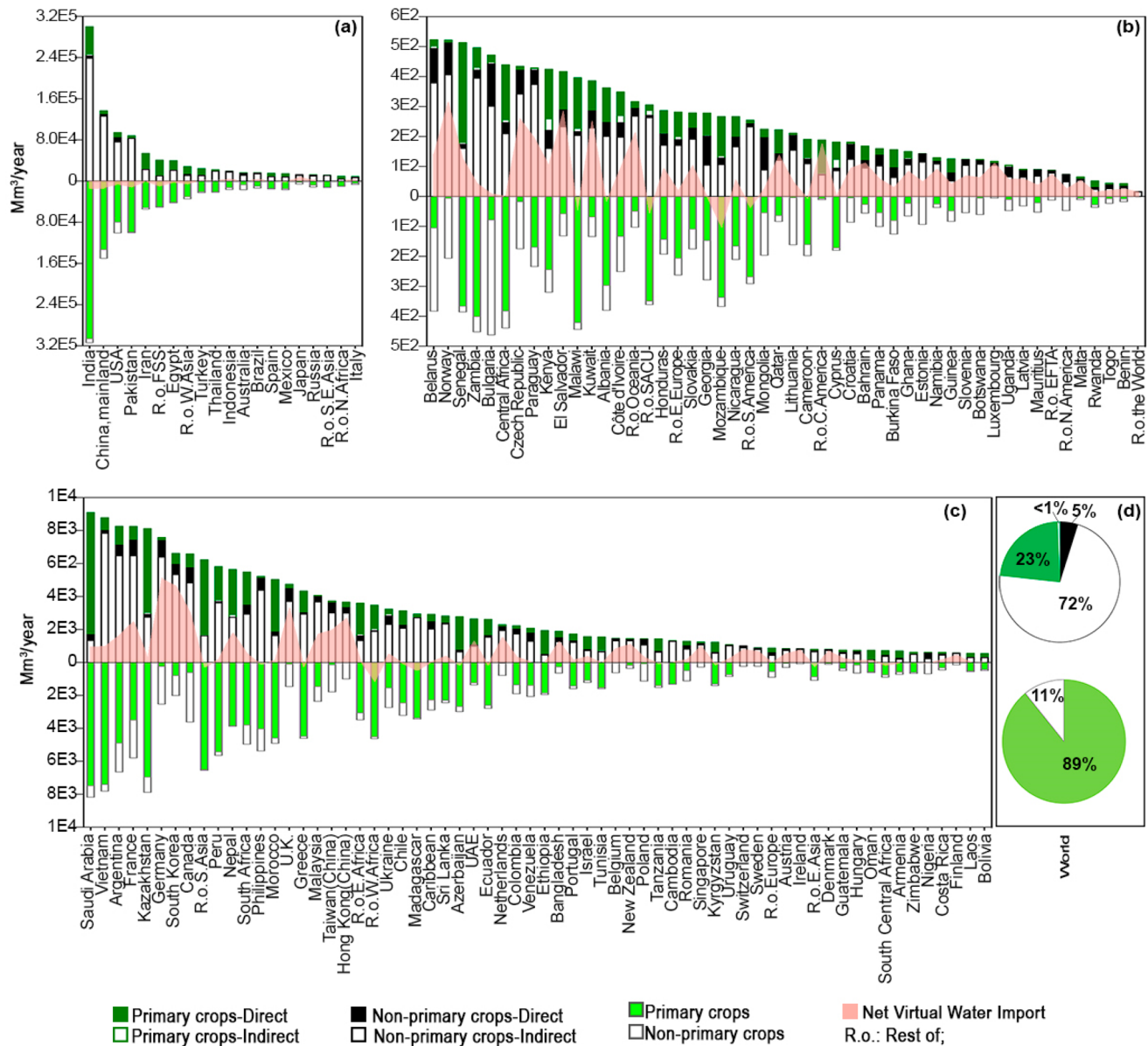


Figure 2. National blue water footprints (WF_b, “0” and Above) and production-based blue water consumption (PWC_b, “0” and Below) shown in three clusters according to the WF_b of top 20 (a), bottom 40 (b), and the rest of regions in between (c). Each WF_b bar is made up by WF_b associated with finished primary crop products and nonprimary crop products consumed by each nation, causing direct and indirect water consumption along the entire supply chain. Each PWC_b bar is shown by the primary crop products and nonprimary crop products produced within each nation, which directly consumed the blue water. The discrepancies between WF_b and PWC_b represent the net virtual water imports through international trade. Global compositions of WF_b and PWC_b were shown by the top and bottom pie charts in (d), respectively.

crops worldwide and crop production dominated the PWC_b within most countries in 2007, supporting previous findings that over 90% of the world’s freshwater consumption was devoted to food production.^{18,15} However, some regional variations are worth noting, for example, while 95–98% of the blue water consumed within Iran and India was used to irrigate crops, almost all of the water sourced from Belgium and Hong Kong (China) went to nonirrigation activities directly (Figure 2). According to the consumption-based accounts, however, the consumption of primary crop products were only accountable for ~24% of the total water consumption globally. In comparison, >70% of the global blue water flows were consumed at the upstream supply chains for making manufactured products and commercial services, rendering them less visible to both the consumers and policy makers. Across the nations, the various

compositions of WF_b reflect the different consumption patterns from region to region, for example, the consumption of non-processed primary crop products remains a crucial driving force of the national WF_b in several developing regions, such as Iran (57% or 31 Gm³/year) and Egypt (47% or 19 Gm³/year) while the same parameters were 18%, and 2% in India and Germany, respectively.

The WF_b and PWC_b of the Economy: Reallocated Blue Water Consumption throughout the Economy. The direct and indirect freshwater consumption composing the WF_bs and PWC_bs for 57 economic sectors (S1–S57) covering the entire global economy are mapped in Figure 3. Overall, the final consumption (the direct production) of goods and services belonging to “Primary Crops and Livestock”, “Primary Energy and Minerals”, “Processed Food and Beverages”,

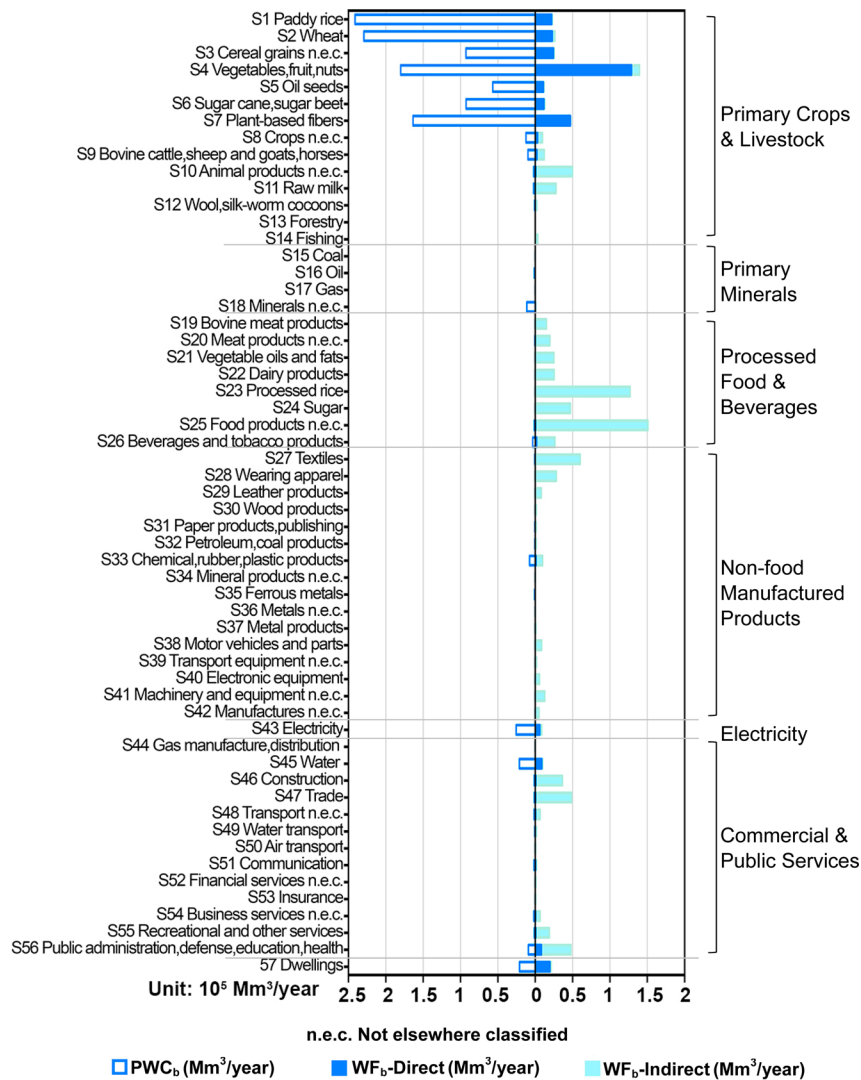


Figure 3. Blue water footprints (WF_b , “0” to Left) and production-based blue water consumption (PWC_b , “0” to Right) of global economic sectors in 2007. Corresponding to the water accounts of WF_b and PWC_b , the economic accounts (\$/y) of sectoral total outputs and final consumer expenditures in 2007 are shown alongside in a secondary axis. Detailed descriptions of Sectors 1–57 are available in the [Supporting Information](#).

“Non-food Manufactured Products”, “Electricity”, “Commercial and Public Services”, and “Households” accounted for 33% (91%), ~ 0% (1%), 37% (<1%), 13% (1%), 1% (2%), 15% (3%), and 2% (2%) of the world’s total blue water consumption, respectively. Comparing the WF_b s and PWC_b s results, it is clear that the vast majority (i.e., over 70%) of water flows did not stop at the primary agricultural sectors serving final consumption, but continued into further manufacturing processes and were ultimately embedded in other finished goods and services. For example, blue water was used irrigating fiber crops but the fiber crops were later made into textile products, which were used for manufacturing automobiles purchased by final consumers; the blue water consumed growing the fiber crops was attributed to Plant-based Fibers (S7) when PWC_b was accounted but allocated to Motor Vehicles and Parts (S38) when WF_b was accounted. The reallocation of water consumption among the economic sectors was largely caused by the indirect blue water consumption upstream the supply chains of finished goods and services: 50%, 19%, and 17% of the indirect water consumption was caused by the final consumption of goods and services belonging to Processed Food and Beverages (S19–26), Commercial and Public Services (S44–56), and

Nonfood Manufactured Products (S27–42), respectively. The direct blue water consumption associated with the finished primary crop products (e.g., irrigating paddy rice, wheat, fresh fruits, etc. the final consumers purchased) and other finished commodities (e.g., water used for making beverages, recreational purposes, at the final stage of the motor vehicles supply chain, at households, etc.) only accounted for 23% (271 Gm³) and 5% (57 Gm³) of global blue water consumption, respectively.

WF_b s of the majority of the 57 commodity sectors (i.e., except S1–7, 18, 43, 44, and 57, representing primary crops, primary minerals, water services, electricity, and household activities, respectively) were dominated by water indirectly consumed in upstream activities (Figure 3). For commodity sectors like “S38 Motor vehicles and parts”, “S40 Electronic equipment”, and “S41 Machinery and equipment n.e.c”, substantial WF_b s (i.e., 40–50%) were embedded in stage-5 and higher order layers upstream the supply chains. Based on the global MRIO framework and the state-of-the-art process-based information for primary agricultural products, this analysis was able to estimate WF_b s by tracing water inputs along the entire supply chain to finished commodities and final consumers with reduced aggregation uncertainty and truncation errors.

Previous studies suggest process-based analysis that “truncates” upstream supply chains systematically underestimates the energy use and CO₂ emission embedded in inputs of capital goods, transport, and services up to 30–50% of the total impact.^{63,64} Our results suggest process-based analysis risk significantly underestimate the WF_{b,s} of processed goods and services, for example, by at least 40–50% for the finished goods and services associated with S38–41 mentioned above. Further, the WF_{b,s} of primary agricultural products, some of which become primary inputs at earlier production stages of industrial and commercial commodities, may be overestimated by the process-based analysis.

Comparing the WF_{b,s} and PWC_{b,s} results also offers insights to the water-energy nexus. According to the production-based water use accounts, energy provisions ranked as the world's third largest water consumer (after irrigation and domestic water supply). According to the consumption-based accounts, however, the energy sectors were not among the major driving forces of the world's water consumption. That is, the demand for various processed commodities and services is driving most of the blue water consumption, rather than intermediate activities such as the irrigation, public water supply, or power generation that were consumed as inputs for finished goods and services belonging to another economic sector. Dependent on the water-intensive supply chains, our results indicate other sectors, such as “S19–S26 Processed Food and Beverages”, “S47 Trade”, “S46 Construction”, and “S56 Public Administration, Defense, Education, and Health” are equally vulnerable, if not more so, to water availability than the sectors whose linkages to water are better recognized (i.e., irrigation, thermoelectric power, and domestic water supply).

Global Virtual Water Trade: Re-evaluating the Patterns and Water Stress Implications. Previous studies, accounting for agricultural products²⁵ or both agricultural and industrial products,¹⁸ reported that 6–13% of global blue water flows were embedded in the international trade. Using the process-based approach, over 70% of transboundary virtual water flows were attributed to the consumption of crop and crop-derived products that were traded internationally.¹⁸ By tracing freshwater flows through a comprehensive intersectoral and inter-regional economic system structure covering all primary and manufactured agricultural, industrial, and commercial goods and services, results from this analysis showed that international virtual water flows accounted for 12% (145 Gm³) of the world's blue water consumption in 2007. Over 50% of the transboundary virtual water flows were ultimately driven by the final demand (as opposed to the intermediate demand of firms for raw materials and other unfinished goods) of manufactured commodities, specifically within the sectors of “S25 Food products n.e.c.” (12–13%), “S28 Wearing apparel” (7%), “S47 Trade” (7%), “Public administration, defense, education, and health” (6%), “S46 Construction” (6%), “S27 Textiles” (5–6%), “S41 Machinery and equipment n.e.c.” (5%), and “S21 Vegetable oils and fats” (5%). **Supporting Information Figure S3** shows the largest gross virtual water flows between any two countries: the virtual water exported from China to Japan (3.7 Gm³/year) was the largest gross international virtual water flow, followed by the ones from the U.S. to Canada (3.2 Gm³/year,) and from China to the U.S. (3.1 Mm³/year). Although the largest gross flows all originated from the blue water directly consumed growing primary crops, most of them were embedded in primary animal products and processed food and nonfood products that were imported to the countries of final consumption.

Focusing on 11 of the world's major crop types, previous research reported most countries consume more of their own blue water than importing it in virtual form.²⁵ Accounting for all primary and manufactured agricultural, industrial, and commercial goods and services, this analysis revealed different patterns. Among the 115 individual sovereignties analyzed, a wide range, that is, 1% ~ 97% (median = 31%) of the national WF_b originated from foreign territories. 89 countries were net blue water importers in international trade (i.e., WF_b > PWC_b, **Figure 2**). For 40 countries, the WF_{b,s} were dominated by the virtual water imported from abroad. Such cross-national significance of virtual water imports were realized by the net outflows from mainland China (13.0 Gm³/yr), India (12.9 Gm³/yr), and Pakistan (11.8 Gm³/yr) that are orders of magnitude larger than most of the net freshwater inflows. Japan (7.3 Gm³/yr), Germany (5.1 Gm³/yr), and Republic of Korea (4.7 Gm³/yr) are among the top net virtual water importers. Depending on the number of crops considered, the method for computing crop water consumption, and the “colors” of water (i.e., blue water: fresh surface and groundwater, green water: rainwater insofar as it does not become runoff²²), previous studies estimated an annual water saving of 164 Gm³ to 450 Gm³ globally^{39,65} and the water savings increased as the trade connections grew over time.²⁰ Our results that 96 Gm³ of blue water or ~8% of the world's blue water consumption were saved due to international trade of agricultural, industrial, and commercial goods and services in 2007 support previous findings. On the country scale, our results further showed that the virtual water trade led to lower domestic water withdrawals in 92 out of the 115 countries, including most of those where the country-level water stress are moderate and higher during 2000–2014 (i.e., WSI_C > 0.2). That is, without international trade and based on the countries' own production structure, water use efficiency, and climate conditions, current commodity consumption patterns in these countries would result in additional blue water withdrawn from the domestic water environments (i.e., WW^{BAU} < WW^{NT}), some of which are already severely or extremely stressed.

Water Stress Implications Across the Basins. The water stress implications of reduced or additional water withdrawal depends on existing water scarcity conditions. Prior WF assessments have commonly used the average w.t.a. ratios on the country scale, that is, a country's total annual freshwater withdrawal as the percentage of its total renewable water resources, to weigh the water flows and distinguish the effects of water withdrawals on stressed and nonstressed waters.^{3,5,66} However, the spatial distribution of freshwater resources and vulnerabilities to water scarcity are highly uneven at the basin scale within a country,^{67,68} highlighting the importance of a basin-scale assessment for the water stress implications of global virtual water trade.

As **Figure 4** and **Figure S4** shows, the basin-level water stress levels and their changes due to virtual water trade (i.e., ΔWSI_i) vary greatly within most countries. Assuming the additional increases or reductions of a country/region's water withdrawals without international trade (i.e., WW^{NT}–WW^{BAU}) would be distributed among all basins within its territory according to the magnitudes of current basin-level water withdrawal (i.e., WW_i^{BAU}), ΔWSI_is are more significant for areas where the stress levels are already high. Intuitively, areas where existing water withdrawals are concentrated and exerting high pressure on available water resources are more sensitive to additional increases or decreases of water withdrawals. Six regional “hotspots”, where virtual

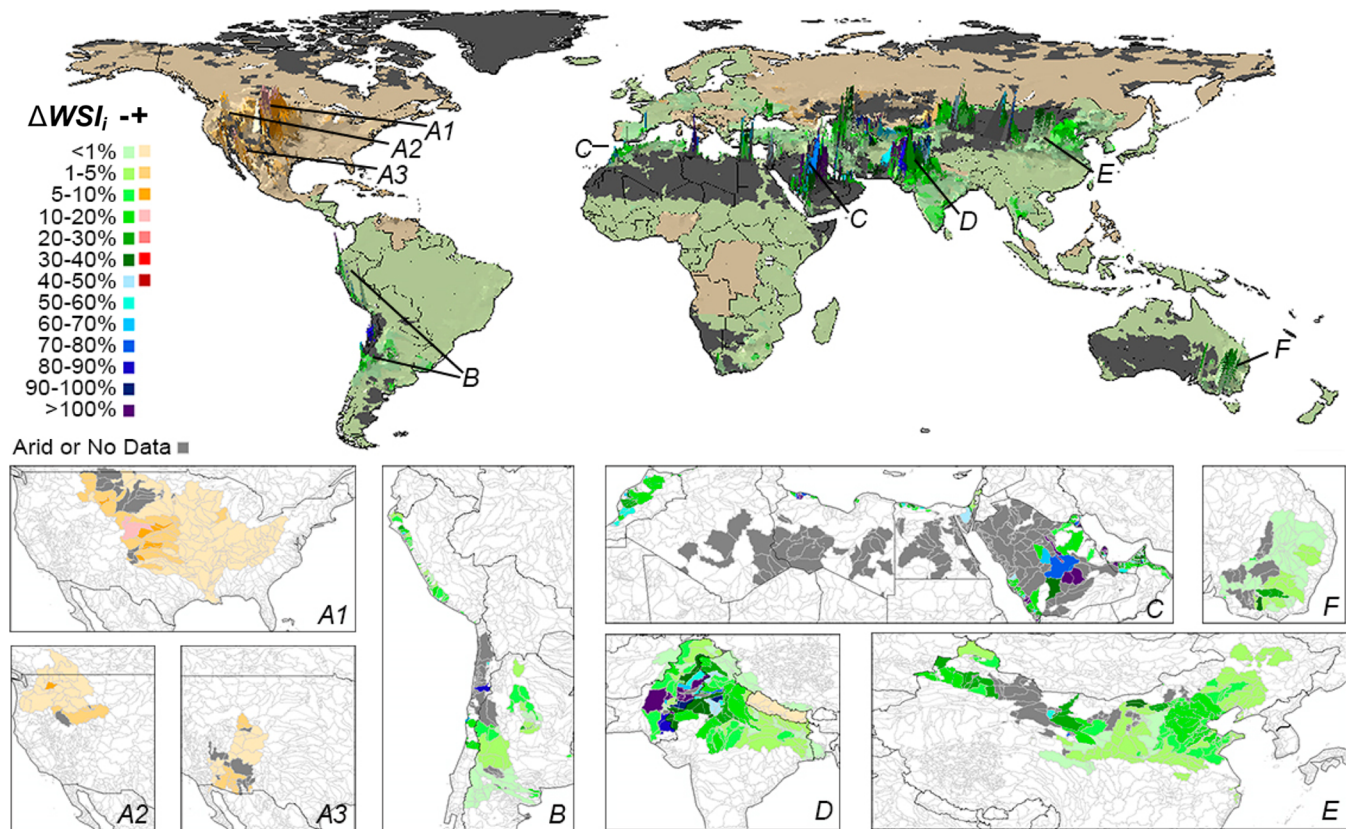


Figure 4. Basin-level water stress changes attributable to international trade (\pm : increase/decrease of blue water withdrawal as a fraction of the renewable blue water resource within a basin). **Top:** Worldwide changes; topography reflects WSI_i^{BAU} , that is, higher latitude indicates higher water scarcity and vice versa. **Bottom:** Regional hotspots, specifically, in A (North America) 1. The Mississippi River Basin, 2. The Columbia River Basin, and 3. The Colorado River Basin; B. Peru, Chile, and Argentina; C. Middle East; D. The Ganges River Basin and The Indus River Basins; E. China; F. The Murray-Darling Basin.

water trade made substantial impacts on some of the world's most stressed water environments, are highlighted in Figure 4. Specifically, within the basins of Mississippi River, Columbia River, Colorado River in North America, virtual water trade of the United States and Mexico resulted in additional water withdrawals in some of the already extremely stressed basins (i.e., $WW_i^{BAU} > WW_i^{NT}$), which are up to 15%, 6%, and 3% of the renewable water resources available in the sub-basins, respectively. In many more basins where existing water stress levels are severe to extreme (i.e., $WSI_i^{BAU} > 0.4$), the virtual water trade mitigated the water stress levels that would be even higher if virtual water trade was absent. An additional 10–80% of the renewable water resources within some of the extremely stressed areas, for example, in the basins of Canete River (Peru), the Colorado River (Argentina and Chile), Lake Mar Chiquita (Argentina), the Black River (Argentina), the Limari River (Chile), the Yellow River (China), the Yongding River (China), and the Luan River (China), would have to be withdrawn to support the countries' current consumption patterns in the absence of trade. Within the Murray-Darling Basin in Australia, up to 30% of the renewable water resources were not removed from the basin due to virtual water trading. The virtual water trade realized the most significant stress alleviation in several naturally arid Middle East and North African countries and within the Indus and Ganges Basins in India and Pakistan. However, the much reduced water withdrawals did not prevent the excessive overdrafts and depletion already ongoing in the Ganges.

DISCUSSION

Relying on extensive physical and economic data inputs, varying assumptions, and methodological approaches that are still evolving, considerable variability is expected for different WF estimates (Supporting Information Table S1). Without sufficient analyses or clarification, existing WF estimates are significantly disparate causing reasonable skepticism in the robustness and policy relevance of WF accounting.^{32,69} Based on our literature review, one apparent cause of the discrepancies is when WF or virtual water is accounted in some studies, for example, refs 37 and 70 as “water withdrawal”, instead of “water consumption” as initially defined and adopted by most researchers. In some studies, WFs were reported as the aggregated sum of green (i.e., rainwater insofar as it does not become runoff¹²), blue (i.e., fresh surface and groundwater¹²), and gray (i.e., freshwater required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards¹²) WFs (e.g., refs 3) or without any specification of the “color” of the WF assessed (e.g., refs 20 and 32), making interpretation of the WF results controversial and limiting their comparability with estimates from other studies. Studies also relied on conflicting data in international statistics,^{13,71} but the impacts of data quality on the variability of WF estimates are largely unknown. Here, results of the sensitivity analysis, where the water consumption coefficients of thermoelectricity generation were varied by $\pm 50\%$ for each country separately and all countries simultaneously, suggest the main findings of this analysis are robust. Across countries, changes of the coefficients did not affect

the overall pattern and the large players of WF_b or PWC_b (Supporting Information Figure S5); across the 57 economic sectors, the patterns of WF_b , PWC_b and WF_b vs PWC_b were not affected, although the absolute values of WF_b and PWC_b for Sector 43 Electricity changed considerably (Supporting Information Figure S6).

More importantly, the different WF estimates may suggest different, or even opposing, water management insights. Based on process-based WF accounting that considers direct and some of the secondary blue water consumed in making agricultural and industrial products, primary crop products dominate the international virtual water flows for the U.S., Germany, and globally (Figure 5). However, when the virtual water was traced

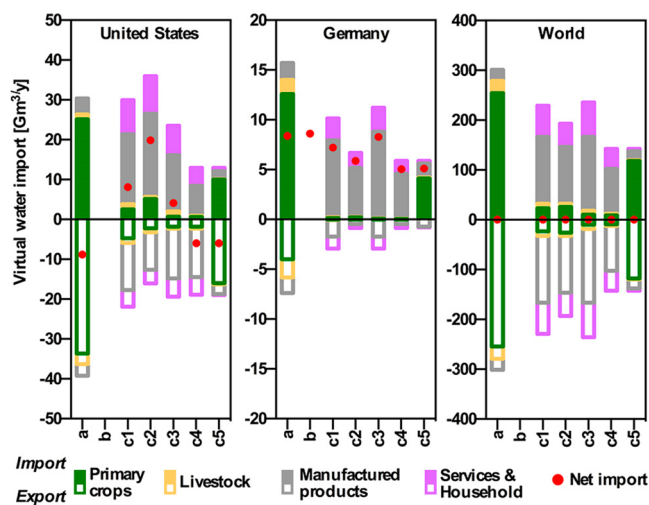


Figure 5. Estimates of virtual water balances (Mm^3/y) for selected regions by comparable WF accounting studies and representative methodological approaches. Virtual water flows were attributed to the direct and indirect blue water consumption by the commodity sectors of “Primary crops”, “Livestock”, “Manufactured products”, and “Services & Household”.

to its final consumers based on the comprehensive intersectoral and inter-regional system structure enabled by the MRIO, the consumption of industrial goods was shown as the largest driver of international virtual water trade. Further, a considerable amount of the virtual water was embedded in service products, which was not captured by the process-based assessment. When the virtual water of the finished goods and services was traced along the multiregional supply chains to producers that directly appropriated and consumed water in the making of intermediate products, as denoted by “Current traced to producers” in Figure 5, it is revealed that the virtual water was largely sourced by/for agricultural practices (i.e., crop irrigation) originally. In another words, national and/or international policies concerning water use and conservation should focus on irrigation efficiency, material and energy use rates, and consumption patterns of finished goods and services, if farmers, manufacturers, and final consumers are to be incentivized or regulated to achieve water conservation goals more effectively.

Based on the same MRIO and water data, national and global virtual water estimates could vary considerably with or without process-based hybridization (Figure 5). These discrepancies highlight that the virtual water trade flows, the balance (even the + or – signs), and thus potential policy implications are quite sensitive to the methodological specifications adopted. As illustrated in Figure 5, the U.S. varied between a net virtual

water importer and exporter depending on the data sources and sectoral resolution. However, a thorough examination of these discrepancies needs to be built upon information about crop production, trade, and measured water use at a finer spatial resolution, which were often found to be absent or in conflict with the national and international data. The robustness and policy relevance of WF estimates can be most effectively enhanced by improving the measurements of water usage for growing individual crop products, especially in the largest water supplying regions (e.g., India, China, the U.S., and Pakistan), as well as by developing and/or improving the quality of by-sector, intra- and inter-regional trade statistics.

There are other limitations in our work that point to future research needs. This analysis did not consider the water quality impacts of the trade activities. The water quality implications were previously assessed through the gray water footprint, as the volume of freshwater needed to assimilate the pollutant loads to meet existing ambient water quality requirements, while neglecting the temporally- and spatially different baseline water quality and has received considerable criticism.^{72,73} Others have suggested wastewater treatment costs as a more pertinent measure of the water quality impacts.⁷³ It is also worth emphasizing here that there are benefits and limitations to both consumption-based water use accounts as well as traditional hydrological and water management science for policy setting. Policies related to water and water’s nexus with other sectors are formed based on a broad range of factors and policy objectives in physical, social, political, cultural, economic, and various environmental dimensions, and ideally, in an integrative way. However, compared with economic data or even data about other environmental resources (i.e., metal scarcity), there is less information known or available on water use. Moreover, the increasingly consumed water flows are becoming more relevant yet less visible to local stakeholders and national decision makers. The WF_b s estimated in this analysis intend to effectively inform (water, trade, land, infrastructure, etc.) policy making; yet, it will require continuous refinements with better and higher quality data and should be integrated with other factors, such as land, labor, human and physical capital, infrastructure, climate change when establishing water resource management policies.

■ ASSOCIATED CONTENT

📄 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b00571.

Additional information as noted in the text (PDF) (PDF)

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Notes

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