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(Virtual) Water Flows Uphill toward Money

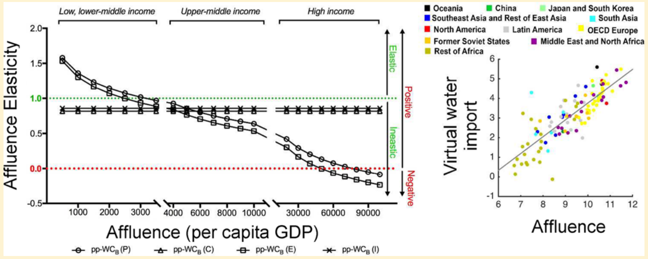
Ranran Wang,[†] Edgar Hertwich,[†] and Julie B. Zimmerman*[,†,‡]

[†]School of Forestry and Environmental Studies, Yale University, New Haven, Connecticut 06520, United States

[‡]Department of Chemical and Environmental Engineering, School of Engineering and Applied Sciences, Yale University, New Haven, Connecticut 06520, United States

Supporting Information

ABSTRACT: This study provides a more precise understanding of the main driving forces of anthropogenic water use across countries. The anthropogenic water use was distinguished as blue water (i.e., fresh surface and groundwater) and total water (i.e. blue + green water; green water is rainwater insofar as it does not become runoff) used for *producing*, *consuming*, *exporting*, and *importing* of primary and manufactured goods and services, measured on a per country and per capita basis. The population effect on national blue water consumption associated with *producing* and *consuming* was found to be bigger than what the commonly assumed unitary population elasticity indicates. Distinct from the homogeneous affluence-water relationships conventionally assumed, this study revealed varying and potentially opposite effects affluence can have depending on the water use account of interest (e.g., production-based or consumption-based, blue or green) and the income level. Affluence, not the availability of freshwater resources, was found to be the most critical driver of virtual water imports. And a more affluent lifestyle in high-income countries was still associated with greater blue water consumption. With each doubling of income, blue water embedded in the goods and services a nation *consumed* and *imported* on a per capita basis increased by 82% and 86%, respectively, across the 110 countries analyzed for 2007. In comparison to affluence, the varying per capita water consumption accounts across the nations were much less sensitive to food consumption patterns. Given its critical role for water, land, and energy use shown by this and previous studies, affluence should be taken as a critical factor in future studies to better understand and leverage the water-energy-food-land nexus.



INTRODUCTION

Anthropogenic activities are exerting growing pressures on freshwater environments from local to global scales.[1−4] Despite this scientific consensus, there is limited understanding of the anthropogenic processes and subsequent policy levers that can effectively mitigate anthropogenic water impacts. For example, the basic question of the main forces driving anthropogenic freshwater use has not been systematically explored. Although it is widely accepted that anthropogenic water uses are governed by population growth, economic development, urbanization, agricultural practices, and the efficiencies of other water use activities,[5,6] the relative significance of these factors remains controversial and incomplete. Historically, broad assumptions based on these general relationships, for example, the monotonic, positive relationships between human water use and economic development or population growth, have led to great discrepancies between the projected and observed water uses.[6] Recent global water assessments, however, still rely on some of these assumptions. For example, the already widely cited latest projection by OECD[7] that global water demand is to increase by 55% by 2050 is based on water use patterns observed several decades ago and assumes almost homogeneous annual technological change rates. In the latest planetary boundary study,[8] the global industrial and municipal water withdrawals were derived from decades-old assumptions and projections with minimal adaptations.

One distinct feature of current and future human water use from the past is the important role of the trade of virtual water, that is, water used in the supply chain-wide production processes of a commodity.[9] Between 1986 and 2007, total virtual water flows embedded in the international trade of food products more than doubled.[10] Without accounting for the "virtual water" embedded in internationally traded goods and services, it has been postulated that the observed stable or declining water usage within mature economies (e.g., the territorial water usage) was evidence of decoupled economic growth and water use.[6,11,12] This would support the Environmental Kuznets Curve hypothesis that "*growth solves environmental problems in the long run*".[1,14,15] Recent research found the similar observed declines in territorial land use and CO_2 emissions could be attributed to "off-shoring".[16−19] By relying on assumptions from past models,[20−23] the implications of globalized trade are still absent from the latest projections of

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human water use at the national and global scales (e.g., refs 5, 7, 8, and 24).

As such, this study aims to advance the understanding of the anthropogenic water use drivers and their relative significance, taking into account the increasingly connected global supply chains underlying the economic systems. A hybrid global water use accounting model with improved spatial coverage and sectoral resolution was used to quantify the anthropogenic freshwater use associated with *producing*, *consuming*, *importing*, and *exporting* of primary and manufactured goods and services, also known as the *production-based (or territorial) freshwater use*, *consumption-based freshwater use (or water footprint)*, *imported virtual water*, and *exported virtual water*, respectively. Multiple regression analyses were conducted to investigate the relationship of each of these four water use categories with a broad range of factors proved or postulated in existing literature as critical determinants of anthropogenic water use. These include socio-economic development status (e.g., population and per capita GDP), natural resource (e.g., land, water) availability, agricultural practices (e.g., cereal production, percentage of irrigated agriculture), food consumption (e.g., per capita calorie supply from various food sources), as well as indicators of economic and water use structure (e.g., percentages of GDP generated or freshwater withdrawn by main economic sectors). The cross-national *per-country* and *per-capita* analyses explicitly distinguishes between blue water (i.e., fresh surface and groundwater) and green water (i.e., rainwater insofar as it does not become runoff),[25] as well as freshwater consumption and freshwater withdrawal following the USGS definition.[26]

This study improved upon existing literature in a number of respects. Primarily, this analysis is the first to compare the cross-national relationships of both *territorial* and *consumption-based* water usage, on a per capita and per country basis, with a broad range of potential explanatory variables. Additionally, this study provided a more precise understanding of the drivers of global virtual water trade where these were previously (e.g., refs 10 and 27−30) understood based on bilateral trade records, often did not distinguish green and blue water, and focused on the freshwater flows embedded in a number of crop and animal products, thus ignoring manufactured products and services. Using the global multiregional input-output (MRIO) dataset that recently became available, this analysis was based on the virtual water embedded in all goods and services traded globally. As such, the virtual water flows accounted here have taken into consideration not only industrial products and services but also the agricultural products that, increasingly, have become inputs to other food products, industrial goods, and services, and traded to other countries. Further, given that blue water is generally regarded as of higher value than green water,[31] yet green water dominates most national total water consumption accounts (e.g., green water could be 2−5 times of blue water), there was an explicit distinction between blue and green water in this analysis. The results demonstrate that the governing factors and their effects on virtual water trade varied depending on the "color" of the water accounted. Recognizing the differences between water withdrawal and water consumption (i.e., the latter could be 10~90% of the former depending on the water use activities), the anthropogenic water uses as water withdrawal and water consumption were studied separately.

MATERIALS AND METHODS

Quantifying the Four Anthropogenic Water Use Metrics. The balance that holds for the anthropogenic water uses associated with *producing*, *consuming*, *importing*, and *exporting* of primary and manufactured goods and services is described by eq 1.

$$W_{\text{production}} - W_{\text{export}} + W_{\text{import}} = W_{\text{consumption}} \tag{1}$$

The four anthropogenic water use metrics were quantified using the hybrid global water use accounting model described in ref 32. Briefly, the model is based on the multiregional input-output (MRIO) tables retrieved from the GTAP 8 database, which describes 134 countries/regions with 57 economic sectors covering the entire global economy for the base year of 2007.[33] It achieves a higher level of sectoral resolution by enhancing the eight sectors representing aggregates of primary crop products with the production and trade data of 209 individual primary crop products obtained from FAOSTAT.[34] Using the model, the four water use metrics for each of the 134 countries/regions were quantified distinguishing blue water and total water (i.e., blue + green water), and water consumption and water withdrawal, respectively. Among the 134 regions/countries, 114 are individual sovereignties and 20 are composite regions. In the following analysis, the results focused on the 114 individual sovereignties (referred to as "countries").

Multiple Regression Analysis using the STIRPAT Model. The main drivers of the various anthropogenic water use categories were investigated using multiple regression analysis, more specifically, based on the STIRPAT model. The STIRPAT model has been successfully utilized to investigate the main driving forces of other environmental issues, such as energy use,[35] CO_2 emissions,[36] land use,[18] and air quality.[37] Detailed descriptions of the STIRPAT model are available in ref 35. Briefly, the STIRPAT model was developed from the IPAT identity ($I = PAT$)[38] that is still widely used as the framework to illustrate how environmental impacts (I) are affected by the key driving forces: P = population, A = affluence, and T = technology or per unit impact of production or consumption. As an improvement from the IPAT model, STIRPAT model (eq 2) and the commonly used natural logarithmic form (eq 3)[35] can more precisely specify the sensitivity of the environmental impacts to each driving force.

$$I_i = aP_i^bA_i^cT_i^de_i \tag{2}$$

$$\ln I_i = a + b(\ln P_i) + c(\ln A_i) + e_i \tag{3}$$

In the STIRPAT model, the constant a, and the coefficients b, c, and d are all estimated; e is the error term. Each coefficient is an empirical estimate of the "ecological elasticity", indicating the responsiveness or sensitivity of the environmental impacts (i.e., the dependent variables) to a change in any of the drivers (i.e., independent variables). In the natural log form (eq 3), the coefficient or ecological elasticity indicates the proportional change (in percentages) in the dependent variable (i.e., *Impact*) from a one-percent change in an independent variable with other factors held constant. A coefficient equal to 1.0 (or −1.0) indicates positive (or negative) "unit inelasticity", meaning a percentage change in the driving force produces an positive (or negative) identical percentage change in the impact. Coefficients >1.0 (or < −1.0) suggest a positive (or negative) "elastic" relationship, where the impact increases (or decreases) more rapidly than the increases of the driving forces.

Table 1. **Overview of the Observed Water Consumption, On a Per Country (*WC*) and Per Capita (pp-WC) Basis, Associated with *Producing* (P), *Consuming* (C), *Importing* (I), and *Exporting* (E) of Primary and Manufactured Goods in 2007**[a]

	global total (Gm^3)	coverage (by 110 countries)	range (Mm^3 or m^3/person)	average (Mm^3 or m^3/person)	median (Mm^3 or m^3/person)
WC (P)	1194 (7295)	88% (88%)	6-213 673 (39–1 257 054)	9588 (58 198)	662 (13 335)
WC (C)	1194 (7295)	89% (88%)	66–300 790 (424–1 213 206)	9686 (58 361)	1056 (15 693)
WC (E)	144 (992)	83% (88%)	1–26 505 (3–171 772)	1095 (7878)	109 (1398)
WC (I)	144 (992)	91% (89%)	19–13 460 (106–97 405)	1194 (8041)	290 (2544)
pp-WC (P)			2–788 (58–4918)	118 (1054)	60 (886)
pp-WC (C)			4–783 (181–5213)	148 (1214)	102 (1044)
pp-WC (E)			0–119 (3–2070)	16 (167)	9 (105)
pp-WC (I)			1–270 (6–2790)	46 (327)	26 (171)

[a] Blue and total (*parenthesized*) water consumption were distinguished. *Global Total* accounts for the global water consumption by all 134 countries/regions specified in GTAP 8. 88–91% of the global accounts were covered by the 110 countries analyzed in the regression analyses this study performed.

Coefficients <1.0 but >0 (or > −1.0 but <0) indicate "inelasticity", where the impact increases (or decreases) in lesser proportion to an increase in the driving force. As such, STIRPAT model can empirically test hypotheses of the effects from various anthropogenic drivers, revealing the potentially varying elasticity/inelasticity at different points of *Population*, *Affluence*, and *Technology* (as opposed to the mathematical identities and proportionality constraints, $a = b = c = d = 1$, assumed in IPAT). Since T represents everything that is not *Population* or *Affluence* and there is no agreed-upon operational measure of T, it has been typically solved using known I, P, and A in an IPAT model. Consistent with the IPAT model, T is often included in the error term e in a basic STIRPAT model (see eq 3). In an expanded STIRPAT model, the effects of T are commonly addressed by including a variety of additional variables that potentially influence the impact per unit of production or consumption, equivalent to disaggregating T. As such, the STIRPAT model can help advance the basic science of environmental change, as well as more precisely reveal the factors that may be more responsive to policy.[35]

eq 4 and eq 5 represent the regression models this study used to analyze the anthropogenic water use on a per country (W) and per person (pp$W$) basis, respectively. Freshwater use associated with *producing*, *consuming*, *importing*, and *exporting* of primary and manufactured goods and services on a *per-country* and *per-person* basis were the dependent variables. The freshwater usage explicitly distinguished as *blue* or *total* water (i.e., the sum of blue and green water), and water withdrawal or consumption was tested in each regression analysis.

$$\log W = \alpha + \gamma(\log P) + \delta(\log A) + \beta_1(\log x_1) + \beta_2(\log x_2) + \beta_3(\log x_3)... + \varepsilon \tag{4}$$

$$\log \mathrm{pp}W = \alpha_{pp} + \delta_{\mathrm{pp}}(\log A) + \beta_{1,\mathrm{pp}}(\log x_1) + \beta_{2,\mathrm{pp}}(\log x_2) + \beta_{3,\mathrm{pp}}(\log x_3)... + \varepsilon_{\mathrm{pp}} \tag{5}$$

The independent variables tested in this analysis (i.e., P, A, x_1, x_2, x_3, ...) represent a broad range of factors, including (in year 2007) socio-economic development status (e.g., population and per capita GDP adjusted by purchasing power parity (PPP[39])), natural resource (e.g., land, arable land, and renewable freshwater) availability, food consumption (e.g., per capita calorie supply from various food sources), as well as indicators of economic and water use structure (e.g., percentages of GDP generated or freshwater withdrawn by main economic sectors). A complete list of the 30 independent variables tested in this study is presented in Table S1. Many of them were found or postulated as critical drivers of anthropogenic water uses in existing literature.[5,6,10,27−30] As a convention of the STIRPAT model,[35] the factors other than population and per capita GDP (*Affluence*) are conceptualized here as components of the technology (T) multiplier that potentially influence the anthropogenic water usage of per unit production or consumption.

Natural log transformations were performed on both the dependent and independent variables (except those measured in percentages) to achieve normal distributions and an easy interpretation of the coefficients. The independent variables were tested and the constants (α or α_{pp}), coefficients (β or β_{pp}, γ or γ_{pp}, δ or δ_{pp}), and error terms (ε or $\varepsilon_{\mathrm{pp}}$) were estimated by performing ordinary least-squares (OLS) regression in SPSS.[40] Using the stepwise algorithm, the entry and removal probabilities in testing the independent variables were 0.01 and 0.05 respectively. 25 of the 30 factors tested were dropped from the models either because they did not have statistically significant effects on any of the dependent variables or to avoid multicollinearity. For the models reported in *Results*, the multicollinearity effect is minor with the highest variance inflation factor (VIF) for any factor in any model being only 1.741.

Data Sources and Assumptions. The food consumption data (i.e., Food supply, in kcal/capita/day) was obtained from the FAO Food Balance Sheet data set[41] and data for the rest of the independent variables were obtained from the World Development Indicators.[42] In order to achieve more accurate comparisons of affluence (i.e., income levels) across countries, per capita GDP was adjusted using the purchasing power parity

(PPP) conversion factors derived from the World Development Indicators.[42] All of the variables are based on the year 2007. When the 2007 data was unavailable for any variable in any country, the average value of the variable observed for the same country between 2001 and 2014 was used. Among the 114 individual sovereignties included in GTAP 8, the regression models reported in *Results* are based on the 110 individual sovereignties where data is available for all of the significant explanatory factors (see Table S2).

Data Uncertainty. Compared with data on the hydrological cycle, data on water use are more variable and incomplete, and frequently contradictory from source to source.[6,13] The amount of freshwater directly withdrawn and consumed for irrigation, of primary importance for water use estimates, is particularly uncertain as it is not metered or reported in most parts of the world. Due to the lack of reliable and reproducible water use data, this study is a cross-sectional analysis.

RESULTS

The Cross-National Variance of Human Water Use: An Overview. Table 1 and Figure S1 provides an overview of the varying blue and total water consumed, on the per country and per capita basis, for *producing*, *consuming*, *exporting*, and *importing* primary and manufactured goods and services. The overview illustrates some of the key nuances associated with the cross-national patterns of human water use, especially the distinctions between the blue and green water, the per country vs per capita perspective. In 2007, 1200 Gm^3 of blue water and 6100 Gm^3 green water were consumed globally, bringing total water consumption to 7300 Gm^3. International trade channeled 145 Gm^3 (12%) of virtual blue water and 992 Gm^3 (14%) of total virtual water. Consistent with previous findings (e.g. refs 43 and 44), green water dominated the total water consumption volume with rain-fed agriculture being the world's predominant agricultural production system.[45] However, blue water is commonly considered to have a higher opportunity cost than green water[29] and has been the sole focus of conventional water use accounting. The freshwater countries consumed for the *production* and *consumption* of primary and manufactured goods varied widely globally and was dominated by a few countries, namely, India, China, and the United States. On a per capita basis (shown by Figure S1B), the ten highest blue and total water consumption rates (m^3/person/year) ranged widely: 320−800 and 2200−5400 m^3/person/year, respectively. They are mostly associated with countries from the Middle East and North Africa (considering only blue water) or Latin America (considering the total water). Although virtual water accounted for a relatively small fraction (1% ∼ 28%) of the 10 highest *production-based* or *consumption-based* water consumption values measured at the country level (Figure S1A), it was a more crucial component for the highest water consumption accounts measured on the per capita basis (Figure S1B). Among the 10 countries with the highest *consumption-based* per capita blue or total water consumption, imports dominated (i.e., > 50%) the blue or total water consumption in the United Arab Emirates, Hong Kong (China), New Zealand, and Singapore.

According to results from the ordinary least-squares (OLS) regression analyses, the governing factors and their effects for the anthropogenic water use variables were similar regardless of whether water withdrawal or consumption was considered, both on a per country and per capita basis. As such, the following analyses focus on water consumption. The results for 16 anthropogenic water consumption accounts including the blue and total water consumption associated with *producing*, *consuming*, *exporting*, and *importing* of primary and manufactured goods and services, on a *per-country* and *per-capita* basis are presented in Tables 2 and 3 and Table S3.

Drivers of National Water Appropriations. The national blue and total water consumption variables were well explained (r^2 = 0.8−0.9) by a few predictor variables: total population, affluence level (represented by per capita GDP, $2007 PPP), the structure of territorial (domestic) water usage, and the availability of arable land (see Figure 1 and Table 2). *Population* was the most significant driver of national water consumption associated with *producing*, *consuming*, and *exporting* of primary and manufactured goods and services. In the most parsimonious models (i.e., population being the only explanatory variable), ∼60% and 70−90% of the cross-national variances for blue and total water were explained, respectively. The regression results further indicate that the blue water use accounts associated with *producing*, *consuming* and *exporting* may increase more rapidly than population (i.e., the *Population* elasticities > 1). This phenomena was previously observed for direct CO_2 emissions at both the national and global scales,[36,46] highlighting the importance of taking into account the disproportionate impact of population change in climate change policy discussions. While supporting the concerns that population increase will lead to continued degradation of freshwater resources, this study suggests that the *Population* effect on human water use may be more significant than the commonly assumed unitary *Population* elasticity. Given human water appropriations generate immediate impacts locally and the locations of production and consumption are becoming further separated, the elastic population-water relationships further suggest that the water resource impacts in *producing* countries, where population growths are anticipated, may be outsize.

For a nation's virtual water import, both *Population* and *Affluence* play a significant role (Table 2). The volume of national blue and total virtual water imports increased by ∼80% with each doubling of total population or average income. For the rest of the water use metrics (i.e., *producing*, *consuming*, and *exporting*), the role of *Affluence* was more complex. Further, the *Affluence* effects appeared to be less or not significant when the total water was accounted (see Table 2), supporting the hypothesis that green water is less economically valued than the already undervalued and underpriced blue water.[47] The relationships between *Affluence* and the per capita water consumption accounts, eliminating the *Population* effects, are further discussed in the next section.

Previously, a nation's agricultural activity was postulated as a more critical determinant for national blue water use patterns and magnitudes than affluence level;[6] however, international virtual total water flows (e.g., blue and green water) were found to be more strongly correlated to the availability of arable land than to that of renewable freshwater.[48] Results from this study (Table 2) revealed that compared to population the various country-level water consumption metrics were much less sensitive to natural resource availability (e.g., the areas of land, agricultural land, or renewable freshwater resources). While the national consumption of total water associated with *producing*, *consuming*, and *exporting* were sensitive to arable land availability (in hectares per person), they only increased by 53%, 21%, and 63%, respectively, for each doubling of arable land availability. Further, natural resource availability appeared

Table 2. OLS Results for National Blue Water Consumption (WC_B) and Total Water Consumption (WC_T) Associated with *Producing* (P), *Consuming* (C), *Importing* (I), and *Exporting* (E) of Primary and Manufactured Goods ($N = 110$, $p < 0.000$)[a]

measure	independent variables tested	r^2	F-statistics	population	affluence	affluence^2	Ag.%WW	Dom.%WW	arable land availability
WC_B (P)	population	0.70	251	1.192*** (0.075; 0.836)	–	–	–	–	–
	population + affluence	0.77	116	1.167*** (0.069; 0.819)	ns	−0.292*** (0.064; −0.223)	–	–	–
	all (population + affluence + *technology*)	0.90	179	1.078*** (0.050; 0.756)	0.613*** (0.073; 0.350)	-0.152** (0.045; −0.116)	0.022*** (0.003; 0.315)	-0.021*** (0.005; −0.177)	ns
WC_T (P)	population	0.82	482	1.180*** (0.054; 0.904)	–	–	–	–	–
	population + affluence	0.85	203	1.107*** (0.051; 0.848)	−0.324*** (0.066; −0.202)	−0.138** (0.048; −0.115).	–	–	–
	all (population + affluence + *technology*)	0.91	338	1.077*** (0.041; 0.833)	ns	ns	0.008*** (0.003; 0.121)	ns	0.531*** (0.054; 0.302)
WC_B (C)	population	0.69	245	1.020*** (0.065; 0.83)	–	–	–	–	–
	population + affluence	0.81	223	1.119*** (0.054; 0.914)	0.518** (0.066; 0.345)	ns	–	–	–
	all (population + affluence + *technology*)	0.89	279	1.058*** (0.042; 0.864)	0.765*** (0.058; 0.509)	ns	0.020** (0.002; 0.338)	ns	ns
WC_T (C)	population	0.89	889	1.010*** (0.03; 0.94)	–	–	–	–	–
	population + affluence	0.89	889	1.010*** (0.034; 0.944)	ns	ns	–	–	–
	all (population + affluence + *technology*)	0.91	558	0.985*** (0.031; 0.921)	ns	ns	ns	ns	0.210*** (0.042; 0.146)
WC_B (E)	population	0.66	212	1.116*** (0.077; 0.814)	–	–	–	–	–
	population + affluence	0.78	122	1.172*** (0.066; 0.855)	0.393*** (0.086; 0.234)	−0.225*** (0.062; −0.179)	–	–	–
	all (population + affluence + *technology*)	0.84	135	1.045*** (0.060; 0.762)	0.500*** (0.075; 0.297)	-0.165** (0.054; −0.131)	ns	-0.032*** (0.005; −0.278)	ns
WC_T (E)	population	0.68	233	1.116*** (0.073; 0.827)	–	–	–	–	–
	population + affluence	0.70	127	1.101*** (0.071; 0.816)	ns	−0.178** (0.065; −0.144)	–	–	–
	all (population + affluence + *technology*)	0.80	215	1.042*** (0.06; 0.77)	ns	ns	ns	ns	0.628*** (0.079; 0.346)
WC_B (I)	population	0.45	87	0.702*** (0.075; 0.668)	–	–	–	–	–
	population + affluence	0.83	254	0.857*** (0.044; 0.816)	0.816*** (0.053; 0.633)	ns	–	–	–

Table 2. continued

measure	independent variables tested	r^2	F-statistics	population	affluence	affluence^2	Ag.%WW	Dom.%WW	arable land availability
	all (population + affluence + *technology*)	0.83	254	0.857*** (0.044; 0.816)	0.816*** (0.053; 0.633)	ns	ns	ns	ns
WC_T (I)	population	0.44	84	0.693*** (0.076; 0.660)		ns	–	–	–
	population + affluence	0.80	208	0.844*** (0.047; 0.804)	0.794*** (0.058; 0.617)	ns	–	–	–
	all (population + affluence + *technology*)	0.80	208	0.844*** (0.047; 0.804)	0.794*** (0.058; 0.617)	ns	ns	ns	ns

[a] All dependent and independent variables, except those percentage values, were in natural log form. Factors that were significant in one or more models are shown in the table. The affluence variable (i.e., per capita GDP) was centered by subtracting its sample mean (i.e., 9.3) as a common procedure to avoid collinearity between the affluence variable and its quadratic. Ag%WW and Dom%WW are the percentages of agricultural and domestic (or municipal) water withdrawal of a country's total territorial freshwater withdrawal. *Arable land availability* is per capita arable land area. Within the parentheses are standard errors and standardized coefficients, respectively. ns and – indicate the independent variable had non-significant effect and was excluded from the model, respectively. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

to have minimal effects when only blue water was considered. On the other hand, factors that were underrepresented in previous studies did have significant effects on the blue water use metrics. The sectoral structure of a country's territorial blue water withdrawals (i.e., the percentages of agricultural, industrial, and domestic (or municipal) water withdrawal of a country's total freshwater withdrawal), independent of its size, affected its blue water consumption associated with *producing*, *consuming*, and *exporting* of primary and manufactured goods and services. The effects were further analyzed absent of the population effects in the following section.

Drivers of Per Capita Water Appropriations. For all four blue water consumption accounts measured on a per capita basis, the OLS tested a variety of variables including (1) affluence, (2) both affluence and its quadratic form, and (3) 29 independent variables (i.e., all except population). Results are presented in Table 3, indicating that most independent variables dropped out of the stepwise analysis. With the population effects neglected, per capita water consumption indicates a country's water use intensity. Across the 110 countries analyzed, ∼ 50%−70% and ∼20%−65% of the variations of the per capita water consumption accounts can be explained by these variables, respectively, considering blue and total water (Table 3 and Table S3).

Affluence was a significant driver for all of the per capita blue water consumption accounts as well as the total water consumption accounts associated with *importing*. The affluence effects, however, varied among the per capita water use categories and within the range of the observations. For per capita blue water consumption associated with *producing* and *exporting*, the significant and positive coefficients of *Affluence* and the significant and negative coefficients of the quadratic form of *Affluence* suggest inverted "U-shaped" relationships, or potential Environmental Kuznets curves (Figure 2B). At the lower income levels, the inverted "U-shaped" relationships suggest economic development being a stronger driving force, causing a (disproportionally) larger increase of blue water consumption and subsequently more environmental impacts in *producing* countries. At the higher income levels, these regression relationships are consistent with observed declining trends of per capita blue water use for the U.S. and several other developed countries despite continued economic growth.[6,11,13] The OLS results further revealed a turning point at the income level of ∼\$76,300/person/year and ∼\$49,400/person/year (\$2007 PPP) for per capita production-based blue water consumption and blue virtual water export, respectively, where the effects of *Affluence* changed from positive to negative. However, a further examination of the observed income range and the distribution of the countries on the right side of the turning points in Figure 2B weakened the support for the decoupling arguments. As shown in Figure 2B, only Qatar, Luxembourg, and Kuwait surpassed the \$76,300/person/year limit. Half of the countries on or below the declining curve for per capita *virtual water export* are arid, oil-rich countries (i.e., Qatar, Kuwait, and UAE), which do not well represent the overall development patterns for the rest of the world.

The per capita blue water consumption related to the *consuming* activities increased linearly with income, indicating that more affluent lifestyles in high-income countries were still associated with greater blue water consumption. With each doubling of income, blue water embedded in the goods and services a nation *consumed* on a per capita basis increased by

Table 3. Results of the Multiple Regression Analyses for Per Capita Blue Water Consumption (pp-WC_B) Associated with *Producing* (P), *Consuming* (C), *Importing* (I), and *Exporting* (E) of Primary And Manufactured Goods (N = 110)[a]

measure	independent variables tested	r^2	F-statistics	p-value	affluence (Af1)	affluence^2 (Af2)	Ag.%WW	Dom.%WW	arable land availability
pp-WC_B (P)	Af1	0.09	11	0.001	0.297** (0.091; 0.300)	–	–	–	–
	Af1 and 2	0.17	22	0.000	ns	−0.302*** (0.065; −0.408)	–	–	–
	all	0.67	52	0.000	0.598*** (0.070; 0.604)	-0.157** (0.046; −0.212)	0.022*** (0.003; 0.559)	-0.023*** (0.005; −0.345)	ns
pp-WC_B (C)	Af1	0.34	55	0.000	0.485*** (0.065; 0.583)	–	–	–	–
	Af1 and 2	0.34	55	0.000	0.485*** (0.065; 0.583)	ns	–	–	–
	all	0.65	66	0.000	0.817*** (0.060; 0.982)	ns	0.023** (0.002; 0.693)	ns	0.156** (0.057; 0.171)
pp-WC_B (E)	Af1	0.21	28	0.000	0.448*** (0.085; 0.453)	–	–	–	–
	Af1 and 2	0.31	24	0.000	0.333*** (0.085; 0.337)	−0.251*** (0.063; −0.339)	–	–	–
	all	0.52	39	0.000	0.491*** (0.074; 0.497)	-0.167*** (0.054; −0.226)	ns	-0.033*** (0.005; −0.492)	ns
pp-WC_B (I)	Af1	0.70	249	0.000	0.858*** (0.054; 0.835)	–	–	–	–
	Af1 and 2	0.70	249	0.000	0.858*** (0.054; 0.835)	ns	–	–	–
	all	0.70	249	0.000	0.858*** (0.054; 0.835)	ns	ns	ns	ns

[a] All Dependent and independent variables, except those percentage values, were in natural log form. Factors that were significant in one or more models are shown in the table. The affluence variable (i.e., per capita GDP) was centered by subtracting its sample mean (i.e., 9.3) as a common procedure to avoid collinearity between the affluence variable and its quadratic. Ag%WW and Dom%WW are the percentages of agricultural and domestic (or municipal) water withdrawal of a country's total territorial freshwater withdrawal. *Arable land availability* is per capita arable land area. Within the parentheses are standard errors and standardized coefficients, respectively. ns and – indicate the independent variable had non-significant effect and was excluded from the model, respectively. * p < 0.05, ** p < 0.01, *** p < 0.001.

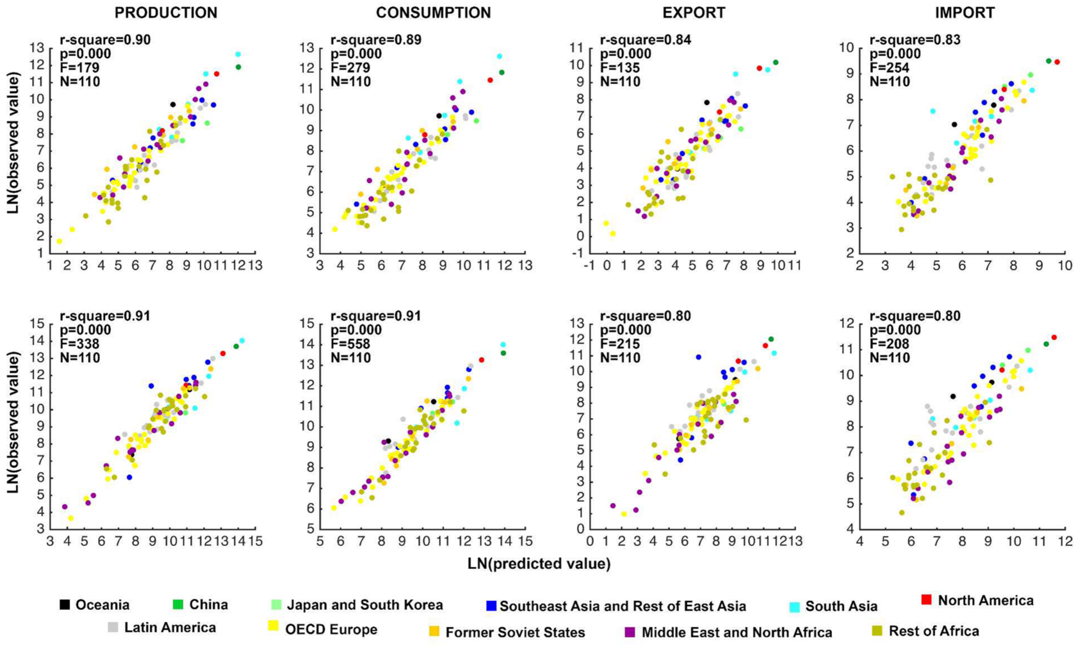

Figure 1. Scatter plots of the observed (y-axis) *versus* predicted (x-axis) values of blue (*top panels*) and total (i.e., blue and green; *bottom panels*) water consumption associated with *Producing*, *Consuming*, *Importing*, and *Exporting* of primary and manufactured goods. The predicted values are based on the regression models where all significant factor(s) were included (see Table 1, i.e., "*All (Affluence + Population + Technology)*". For both the observed and predicted values, the unit is initially Mm^3/year and they were analyzed and presented in the natural logarithmic form.

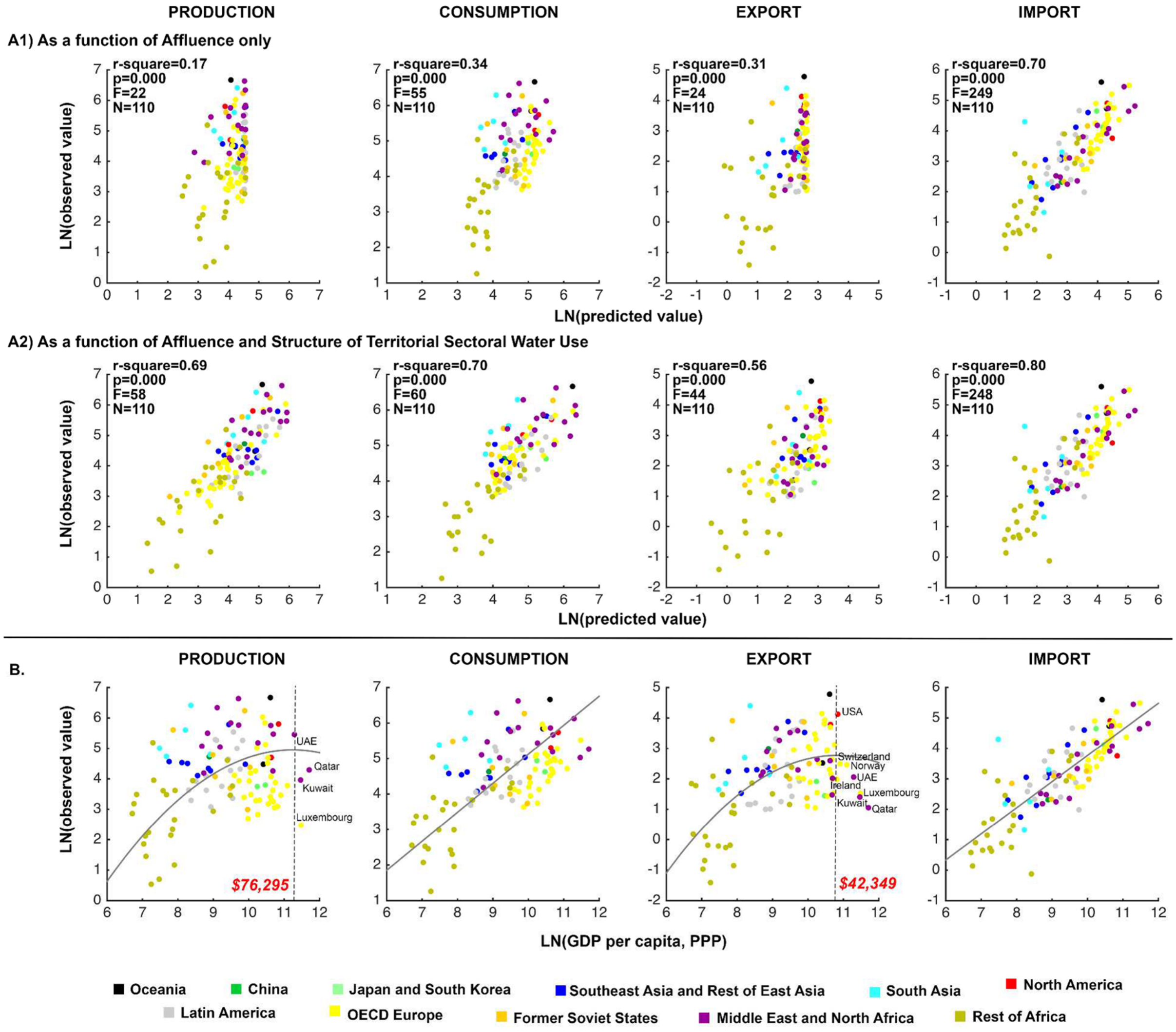

Figure 2. Regression plots of per capita blue water consumption associated with *Producing*, *Consuming*, *Exporting*, and *Importing* of primary and manufactured goods. A. Scatter plots of the observed (y-axis) versus predicted (x-axis) per capita blue water consumption values. The predicted values are a function of (1) Affluence, i.e., GDP per capita and/or (GDP per capita)^2 and (2) Affluence and factors representing the structure of territorial sectoral water withdrawal (as shown in Table 3); B. Observed per capita blue water consumption variables (y-axis) against per capita GDP (x-axis). The solid lines represent the least-squares regression lines based on all significant factors, plotted against GDP per capita, and assuming mean values for the rest of significant factors. The dashed lines and $ represent the turning point, i.e., the income level at which the Affluence effects on the water use accounts change from positive to negative.

82% across the 110 countries analyzed in 2007. This fails to support the Environmental Kuznets Curve hypothesis. Further, the OLS results showed *Affluence* was the most critical driver of the per capita blue and total water consumption related to *importing* activities. With each doubling of income, the blue and total water embedded in the goods and services a nation *imported* on a per capita basis increased by more than 80%. The proposed "decoupling" of domestic water use and economic growth in high-income countries could be, at least in part, attributed to *importing* virtual water through imported goods and services from abroad. Despite the potentially higher need in water-scarce regions, which initially led to the proposal of the virtual water concept, this study suggests virtual water is mainly flowing toward affluence. Water scarcity represented by a country's total and per capita renewable water availability was not a significant determinant of the varying virtual water imports observed in 2007.

Despite the existing perception of the strong water-diet implications, the results here indicate, in comparison to *Affluence*, per capita water consumption was much less sensitive to food consumption patterns. The food consumption variables, that is, per capita calorie supplies from various plants and animal sources or their percentages, did not explain much of the residuals of the per capita water consumption models reported in Table 3 and Table S3. Rather, the few significant food consumption factors that did explain some of the residuals, for example, the calorie supplies from *Meat*, *Wheat*, and *Vegetables,* were highly correlated with affluence. Given that the complex affluence-water relationships were significant in driving water use measured on the per capita basis (i.e., a country's water use intensity), the varying elastic/inelastic and positive/negative effects across the *Affluence* range were plotted in Figure 3. Distinct from the homogeneous affluence-water relationships conventionally assumed, the results highlight the potentially varying water use implications associated with *Affluence* at different economic development stages. Depending on the water use account of interest, for example, blue or total,

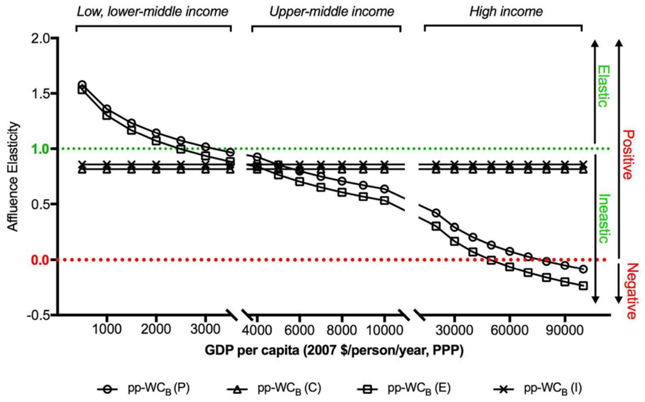

Figure 3. Affluence elasticities, that is, the effects of affluence on per capita water uses associated with *Producing*, *Consuming*, *Importing*, and *Exporting* of primary and manufactured goods at varying affluence levels. The income levels, after adjusting for inflations, were classified based on the new classifications defined by the World Bank.[49]

production-based or consumption based, the affluence effects may be different or even opposite.

As Figure 2A illustrates, the models for per capita blue water consumption associated with *producing*, *consuming*, and *exporting* were greatly improved after incorporating the *T* effects (i.e., the effects of factors other than population and affluence). In particular, the sectoral structure of a country's territorial blue water withdrawal, represented by the absolute values or the percentages of added values from agriculture, manufacturing, and services, were shown to be insignificant. As might be expected, agricultural practices are correlated with higher water demand. However, the results here highlight the importance of building the "agriculture-water use" or "economic sector-water use" relationships upon the sectoral water use structure instead of the sectoral economic structure. This critical distinction is due to the much lower economic productivity of agricultural water usage in comparison to other sectoral water usage. The nonsignificant effect of *percentage value added by agriculture* also indicates the water use productivity of the agricultural activities, as observed in the year 2007, varied greatly among the countries analyzed. The significant and negative coefficients of the percentage domestic water withdrawals, especially regarding per capita blue water footprint, indicates the modernization of a country's water use structure may lead to a true decoupling of economic growth and anthropogenic water use. The modernization of water use structure, for example, through policies focusing on improving the productivity of water use, can increase economic outputs, reduce human water appropriations and the related environmental impacts, all without affecting the agricultural product supply.

■ DISCUSSION

Trade As a Path toward Sustainable Water Development. Although virtual water transfers represent a small fraction of global water consumption (i.e., ~10%), a number of studies revealed a significant amount of blue and green water consumption was avoided by international virtual water trade.[29,50−53] More recently, it was shown that the current international trade patterns resulted in water scarcity mitigation at the basin scale.[32] Further, the water stress mitigation effects of international virtual water trade in 2007 were found to be statistically significant (Wilcoxon Signed-Rank test, at 1% level) across the 12 000 basins globally and within most countries. Unfortunately, the analyses to date have not adequately examined the water quality implications of global supply chains that extend to an increasing number of low-income countries. By considering water quality, the virtual water trade likely has significant environmental and human health relevance that have not been fully explored.

However, to more effectively leverage the water savings and scarcity mitigation potential of virtual water trade, an improved economic valuation of water is essential. Water has long been underpriced[29] with the externality costs (e.g., water pollution) and water scarcity rarely reflected in water prices. The undervaluation relegates water to a low-priority factor in making trade decisions that are governed by comparative advantages measured in economic value.[54−56] As such, forecasts of international trade patterns largely neglect freshwater as a possible constraint to production or as a comparative advantage, resulting in projections of increased agricultural production from already stressed areas, such as North China.[29] In addition to the flawed water pricing schemes, it is critical to note that other factors will play a role in the achievement of full water saving and scarcity mitigation potential of virtual water trade. These include arable land, agro-climate conditions, labor costs, agricultural subsidies prevalent in both industrialized and developing regions, the importance of nearness to market, and the advanced technological competence achieved in some of the water-scarce regions. In the long run, research also cautions that the globalization of water resources could reduce societal resilience by leaving less unutilized water resources to cope with drought.[57] Nevertheless, integrating the potential benefits and impacts of virtual water trade into water demand projections, water scarcity mitigation policies, and pollution control efforts is likely to be increasingly important in achieving sustainable water resource management as population, affluence, and globalization increases.

Affluence and the Water-Energy-Food-Land Nexus. In previous research, affluence was found to be the main driving force for foreign displace land use through international trade of primary and manufactured products and services.[18] The consumption-based energy use was found to not only increase with affluence but at an accelerated rate compared to increases in affluence.[35] The cross-national analyses in this study revealed the decoupling of domestic blue water use and economic growth in high-income countries was realized, at least in part, due to virtual water flows toward affluence and not toward scarcity. In addition, this study revealed the effects of affluence effects were mainly significant for blue, and not for green, water consumption. For blue water consumption, the effects of affluence varied according to income levels and the specific water consumption account considered (e.g., consumption- vs production-based, virtual water imports or exports). The results also support previous concerns that questioned the ability of virtual water transfer to mitigate scarcity from the perspective that less developed, water-scarce countries may not be able to fully participate in international trade.[58] Given the critical role of affluence for water, land, and energy use, we propose affluence should be taken as a critical determinant in future studies on the water-energy-food-land nexus. The revealed effects of affluence on water in this analysis and on land and energy in previous studies[18,35,36] suggests affluent regions can continue advancing economic growth while minimizing domestic impacts, and as a result, the least affluent countries may be further disadvantaged. Through the nexus, the disadvantages of the least affluent countries may interact such that it is greater than the sum of the direct estimate regarding each component. Since affluence inequality is largely missing from existing nexus discussions, the understanding of the nexus can be significantly compromised, at best limiting the effects of subsequent policy or technological solutions and worst contributing to unintended consequences.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b03343.

Additional information as noted in the text (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: Julie.zimmerman@yale.edu.

Notes

The authors declare no competing financial interest.

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