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Virtual water transfers unlikely to redress inequality in global water use

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Abstract
The distribution of renewable freshwater resources between countries is highly unequal and 80% of humanity lives in regions where water security is threatened. The transfer of agricultural and industrial products to areas where water is limited through global trade may have potential for redressing water imbalances. These transfers represent 'virtual water' used in commodity production. We evaluated the current water-use inequality between countries and the potential of virtual water transfers to equalize water use among nations using multiple statistical measures of inequality. Overall, the actual use of renewable water resources is relatively equal even though the physical distribution of renewable water resources is highly unequal. Most inequality (76%) in water use is due to agricultural production and can be attributed to climate and arable land availability, not social development status. Virtual water use is highly unequal and is almost completely explained by social development status. Virtual water transfer is unlikely to increase water-use equality primarily because agricultural water use dominates national water needs and cannot be completely compensated by virtual water transfers.

Keywords: virtual water, water footprint, inequality, water use, Gini coefficient

1. Introduction

If all countries relied only on their internal freshwater resources, some countries would not control enough water to support their current population and standard of living (Allan 1998). These countries can balance their water needs by importing virtual water through the international trade of agricultural and industrial products (Allan 1998, Chapagain and Hoekstra 2004). The virtual water required to support international trade is the volume of water used to produce, but not necessarily contained within, a unit mass of agricultural and industrial goods (Allan 1998, Chapagain and Hoekstra 2004). The concept of virtual water is analogous to the concepts of embodied carbon and embodied energy (Lenzen 2009).

Virtual water transfer is thought to 'save' water (352 $Gm^3\ y^{-1}$ globally) because crops can be grown in water-use efficient environments and exported to other countries with greater water-use requirements for the same crop (Chapagain *et al* 2006). The transfer of virtual water between countries has also been credited with preventing wars over freshwater resources because it is less expensive to participate in international trade than to battle for water resources (Allan 2002, Barnaby 2009). Despite the potential importance of these indirect water transfers, the concept of virtual water has not been actively employed as a policy tool to avoid conflict because water is not generally the dominant factor in making trade decisions (Allan 1998, Wichelns 2010).

The number of people subject to water shortages is increasing and a greater proportion of the water-scarce population is subject to more severe shortages (Kummu *et al* 2010). The average standard of living is based on mean use and quantitative measures of inequality, and a recent United Nations report concluded that inequality, with poverty, unequal power relationships, and flawed water management policies, exacerbates water scarcity (Bishop *et al* 1991, UNDP 2006). A greater level of inequality corresponds to a lower average standard of living if average water use is held constant (Bishop *et al* 1991). At a global scale, given growing population and a finite volume of renewable freshwater resources, a more equal distribution of water use between countries may be necessary in order to ensure that the global standard of living is at least 1000 $m^3\ y^{-1}$, the volume of water defined by some as a human right (Zeitoun 2009, Gleick 1998, Kumar and Singh

2005, Islam *et al* 2007). As originally proposed, virtual water should flow down gradients of resource endowments from water-rich to water-scarce regions (Allan 1998). While not considered directly in early work (e.g. Allan 1998), these flows have the potential make water use between countries more equal because water-scarce populations can, in effect, receive water subsidies from water-rich countries through international trade. However, the ability of virtual water transfer to benefit water-scarce countries has been questioned because poor, water-scarce countries may be unable to participate in international trade (Ioris 2004). Further, international trade is governed by comparative advantages, not absolute advantages of resource endowments (Wichelns 2010, 2004). The theory of comparative advantages shows that water-scarce countries may not always import virtual water from water-rich countries and may actually export virtual water to other countries, including water-rich countries (Wichelns 2010, 2004). For example, a country that is water-scarce but has a large amount of arable land may have a comparative advantage in crop production over a country that is water-rich but has a high population density and little arable land (Wichelns 2010, 2004, Kumar and Singh 2005). In this case, the water-scarce country might export agricultural products, and as a consequence virtual water, to the water-rich country (Wichelns 2010, 2004). Further, trade decisions are not generally based on water needs. Rather, virtual water transfer is a side effect of trade decisions for other resources and thus these transfers might not be efficient from a water use perspective. Yang *et al* (2003) found a strong relationship between water availability and net cereal imports for countries in Asia and Africa, but global simulation and empirical studies have found no relationship between water availability and virtual water trade (Kumar and Singh 2005, Ramirez-Vallejo and Rogers 2004). Thus, it is unclear whether virtual water transfer between countries promotes a more equal water use. Potentially reduced water-use inequality would be a positive benefit of virtual water transfer; however reduced inequality is not a necessary outcome of trade.

Here we assess inequality in water use between nations. We quantify the contribution of different water-use categories to the overall inequality and the inequality within and between social development classes. We conclude that virtual water transfer is not sufficient to equalize water use among nations primarily because internal agricultural water use, the main contributor to inequality, dominates national water needs and cannot be completely compensated by current volumes of virtual water transfers.

2. Methods

We retrieved United Nations data on total renewable water resources, agricultural water footprint, industrial water footprint, household use water footprint, population, reference evapotranspiration and arable land. We describe these data briefly here; detailed descriptions of the primary data sources and methods, including equations and schematic diagrams, are available in Chapagain and Hoekstra (2004), Hoekstra and Chapagain (2007) and Chapagain and Hoekstra (2008). These data are available online at www.waterfootprint.org. Total renewable water resources ($m^3\ y^{-1}$) include all renewable water resources within and on a country's borders (e.g. lakes, rivers, rechargeable aquifers). The total water footprint is the volume of water necessary to support the population of a country including household water uses, water to grow the agricultural products the population uses, and water to produce the industrial products the population uses. The total water footprint ($m^3\ y^{-1}$) is the sum of internal and external water footprints ($m^3\ y^{-1}$). The internal water footprint is the volume of water used for household needs, for agricultural production within the country's borders, and for industrial production within the country's borders. The external water footprint is the volume of water used to produce agricultural and industrial products elsewhere that are imported into the country. The external water footprint is equivalent to the virtual water import of the country. Reference evapotranspiration describes evapotranspiration ($mm\ y^{-1}$) from a hypothetical vegetated surface achieving full production based on climatic parameters. We used the single reference evapotranspiration value for each country calculated by Chapagain and Hoekstra (2004). This value is independent of crop type and soil type but serves as a useful indicator of potential climatic influence on crop production.

We retrieved United Nations human development index values for each country. The human development index is a composite index of national social and human development status based on economic success, healthcare, and education (Chen *et al* 2010). The human development index ranges from 0 (lowest possible level of development) to 1 (highest possible level of development). We divided countries into three social development levels by human development index: highly developed nations (human development index 0.800–1), developed nations (human development index 0.500–0.799), and lesser developed nations (human development index < 0.500) (Chen *et al* 2010). Countries with no human development index due to a lack of data ($n = 7$) were assigned to the lesser developed nation category.

We plotted Lorenz curves for internal (household use, agricultural, industrial) and external (agricultural, industrial) water footprints (see below, Yao 1999). For each water use, the Lorenz curve is the cumulative proportion of water used by the cumulative proportion of global population. For example, figure 1 displays several hypothetical Lorenz curves (green, blue, and red curves). When there is no inequality (i.e. 20% of the population uses 20% of the water, 30% of the population uses 30% of the water, and so on) the Lorenz curve is diagonal (black curve). When the Lorenz curve is concave (figure 1, red, green, and blue curves) there is inequality (e.g. 20% of the population uses 10% of the water). The Gini coefficient is twice the area between a reference diagonal line of equality (black curve) and a Lorenz curve. There is perfect equality when the Gini coefficient equals 0 and perfect inequality when the Gini coefficient equals 1.

Lorenz curves with different shapes can have the same Gini coefficient. For example, in figure 1 the blue and green Lorenz curves have equal Gini coefficients and equal means but describe very differently shaped distributions. The blue curve is an example of a distribution where inequality is due

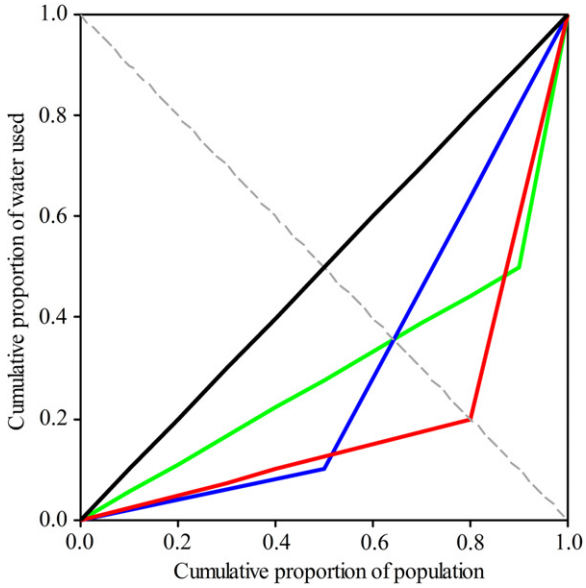

Figure 1. Hypothetical Lorenz curves. The black line is the line of equality (e.g. 20% of the population uses 20% of water, 30% of the population uses 30% of water, and so on). The dashed gray line is the line of symmetry. The blue and green hypothetical Lorenz curves have the same amount of inequality (same Gini coefficient) but have different shapes described by an asymmetry coefficient ($S < 1$ for the blue curve and $S > 1$ for the green curve). The red hypothetical Lorenz curve has greater inequality (larger Gini coefficient) than the blue and green curves but is symmetrical ($S = 1$).

to a large number of low water-use countries (approximately 50% of the population uses 10% of the water). The green curve is an example of a distribution where inequality is due to a few countries over-consuming (approximately ten per cent of the population uses 50% of the water). We describe the shape of the distributions using the Lorenz curve asymmetry coefficient (Damgaard and Weiner 2000). An asymmetry coefficient $S < 1$ describes a curve where the point with a slope of one is below a line of symmetry (gray dashed line in figure 1) such as the blue Lorenz curve (figure 1). An asymmetry coefficient $S > 1$ describes a curve where the point with a slope of one is above the line of symmetry such as the green Lorenz curve (figure 1). An asymmetry coefficient $S = 1$ represents a symmetrical curve such as the red Lorenz curve in figure 1. We also calculate the Hoover index, which is equivalent to the maximum vertical distance between the diagonal line of equality and the Lorenz curve, and can be interpreted as the proportion of water used by above average water users that would have to be redistributed to low water users in order to achieve an equal distribution (Hoover 1941, White 1986). The overall water footprint can be decomposed by water-use type and between development classes (Yao 1999). We first decompose the overall Gini coefficient by water-use type (Yao 1999). This approach identifies the relative contribution of each water-use type to the overall water-use inequality by balancing differences in mean volume of water and inequality in each group (see Yao 1999 for detailed methodology). We calculated the Gini coefficient for each water use and then decomposed these Gini coefficients by social development class (Yao 1999). This decomposition allows identification of the share of inequality in each water use due to inequalities between social development classes. If a relatively large share (e.g. >50%) of inequality originates between development classes, inequality in water use can be attributed to the social, economic, and historic factors that separate countries in terms of development status. If only a relatively small share (e.g. <25%) of inequality originates between development classes, inequality in water use can be attributed to causes other than development status. The statistics in this analysis measure inequality in water use but do not address ethical issues or values relating to water-use inequality. Discussion of equity in terms of water use can be found in Hoekstra (2011), Zehnder *et al* (2003).

3. Results and discussion

3.1. Decomposition by water use

Overall, inequality in water use is relatively minor (total water footprint Gini coefficient = 0.226) compared to the natural inequality imposed by geography and climate in the distribution of total renewable freshwater resources between nations (Gini coefficient = 0.649) (figure 2(A)). This is because water-rich countries do not fully exploit their renewable freshwater resources.

Individual water-use categories do not necessarily have to be equal in order to achieve an overall equal water use. However, the drivers of inequality within water-use categories may be different and hence it is useful to analyze data in these categories to uncover relationships that may be hidden when examining total water footprints. Internal industrial production, household use, agricultural imports, and industrial imports are all highly unequal (table 1, figure 2(B)) but account for only minor portions (24% combined) of the overall water-use inequality (figure 3(A)). Internal agricultural production is the least unequal water use (table 1) but dominates the overall inequality because the mean per capita water use in this category is one to two orders of magnitude greater than the other water uses (table 1, figure 3(A)). Thus the distribution of industrial and virtual water has little impact on the overall inequality in water use despite being highly unequal. Lorenz curves for different water uses are relatively symmetric. The Lorenz curve asymmetry coefficients are all less than 1, indicating that inequality in water use is not caused by overuse by a few countries but rather by an abundance of low water use countries (Chen *et al* 2010). This is in contrast to other renewable resource exploitation and non-renewable energy resource exploitation patterns which are dominated by a few high use countries (Chen *et al* 2010).

The Hoover coefficients, which provide a more straightforward interpretation of inequality than the Gini coefficient, also show considerable inequality in water use with as much as 65% of industrial water needing to be redistributed from the water-rich to water-scarce nations to equalize water use (table 1). However, only 20% of water would need to be redistributed from water-rich to water-scarce nations for agricultural production, the largest volume use. The

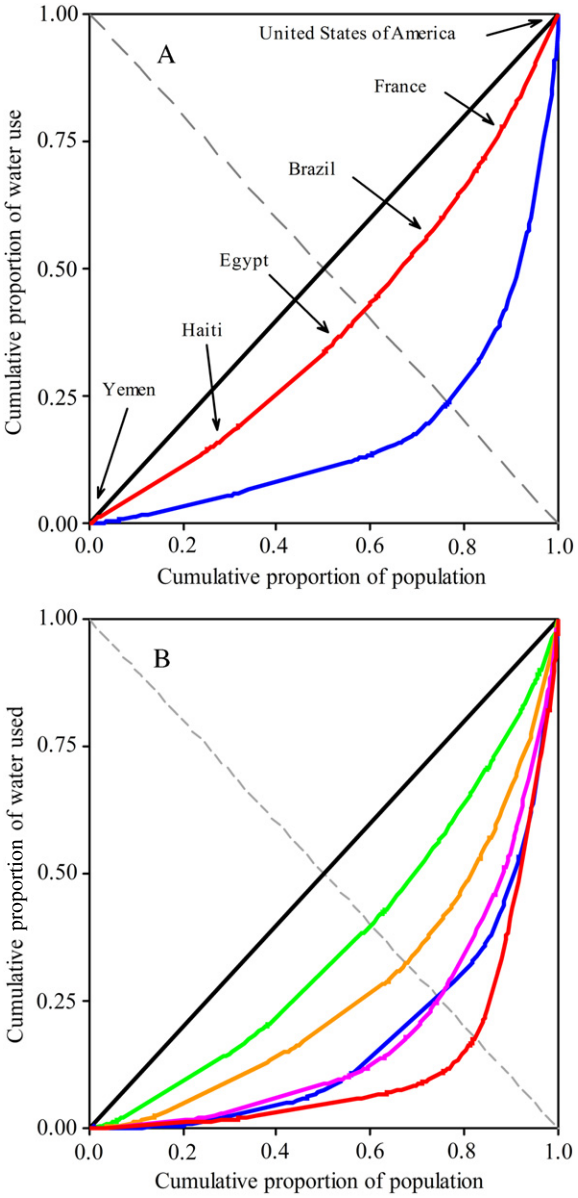

Figure 2. (A) Lorenz curves for total water footprint (red) and total renewable water resources (blue). The locations of water footprints for some representative countries are labeled within the bounds of this figure. The United States of America is at the upper extreme of the curve. Countries that fall between France and the United States include Canada and Portugal. Countries that fall toward the middle of the curve, for instance between Egypt and Brazil, include Japan and the United Kingdom. Countries at the lower end of the curve, between Yemen and Haiti, include Afghanistan and Ethiopia. (B) Lorenz curves for five water components of water use. The green Lorenz curve is for the internal agricultural water footprint. The orange Lorenz curve is for household uses water footprint. The blue Lorenz curve is for the internal industrial water footprint. The pink Lorenz curve is for the external agricultural water footprint. The red Lorenz curve is for the external industrial water footprint.

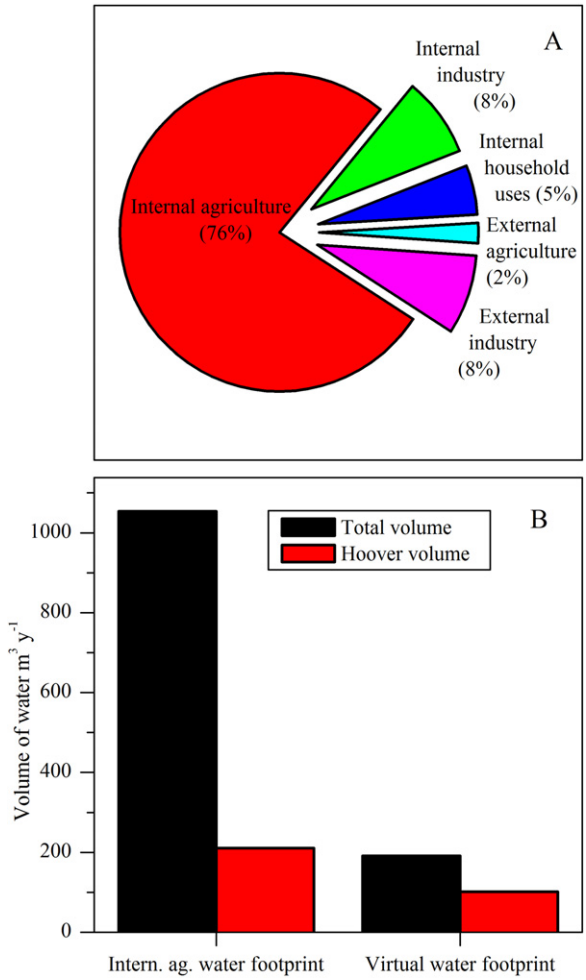

Figure 3. (A) Relative contributions of different water uses to overall water-use inequality among nations. Internal agricultural water footprint dominates the overall inequality. (B) The average internal agricultural water footprint ($m^3\ y^{-1}$) per capita and average volume of virtual water (sum of external agricultural and external industrial water footprints) per capita (black bars). The volume of water needed to be transferred to create an equal distribution, as determined by the Hoover coefficient, is displayed in the red bars and is denoted 'Hoover volume'.

average water use of categories other than internal agricultural production is 370 $m^3\ y^{-1}$ per capita. This distribution would require 181 $m^3\ y^{-1}$ per capita redistributed to achieve an equal distribution. Internal agricultural production has a much higher average use of 1054 $m^3\ y^{-1}$ per capita but would require proportionately less redistribution to achieve an equal distribution (211 $m^3\ y^{-1}$ per capita) (figure 3(B)).

Overall an average of 392 $m^3\ y^{-1}$ of water or virtual water per capita would need to be redistributed in order to achieve an equal distribution. Virtual water transfer currently only accounts for an average of 191 $m^3\ y^{-1}$ per capita of water (figure 3(B)). This potentially represents nearly half the necessary volume of water needed to equalize the water use distribution. However, calculating the Gini coefficient for the total water footprint minus the virtual water footprint gives the same amount of inequality as the total water footprint, indicating that the direction of current virtual water transfers is insufficient to reduce inequality. Thus while the volume of virtual water transfers has the potential to substantially reduce inequality it appears unlikely that the trade of virtual water will alleviate inequality in water use because (1) currently, the volumes of water involved are small enough that there

Table 1. Gini coefficients (G) for different water uses (e.g. internal water footprint (WF) for agriculture). G_a is the intra-social development class (most developed countries, developed countries, least developed countries) component of G. G_b is the between social development class component of G. G_o is the overlap component of G (Yao 1999). There is no overlap ($G_o = 0$) if, for example, the least developed country with the highest water use has a lower water use than the developed country with the lowest water use. The proportional contributions are under the heading 'share of Gini coefficient'. Of particular interest is the share of G_b (denoted G_b/G). When G_b/G is low, social development status and factors that determine social development status do not control the inequality in the water use. When G_b/G is high, social development status and factors that determine social development status control inequality in water use. The mean volume is the mean per capita water consumption ($m^3\ y^{-1}$) for each water use. The asymmetry coefficient is labeled S and the Hoover coefficient is labeled D.

	Components of Gini coefficients				Share of Gini coefficient			Mean volume	Asymmetry coefficient (S)	Hoover coefficient (D)
	G	G_a	G_b	G_o	G_a/G	G_b/G	G_o/G			
Internal WF for agriculture	0.278	0.118	0.052	0.108	0.42	0.19	0.39	1054	0.77	0.20
Internal WF for industry	0.652	0.192	0.410	0.050	0.29	0.63	0.08	121	0.98	0.49
Internal WF for household use	0.626	0.109	0.332	0.185	0.17	0.53	0.3	58	0.74	0.35
External WF for agriculture	0.626	0.160	0.440	0.026	0.26	0.70	0.04	152	0.70	0.5
External WF for industry	0.75	0.146	0.593	0.011	0.2	0.79	0.01	39	0.60	0.65

is not enough virtual water transfer to completely overcome inequalities in internal water use, particularly for internal agricultural production, and (2) the current directions of virtual water transfer do not reduce inequality in the overall water-use distribution.

3.2. Decomposition by development status

The proportion of various inequalities due to differences in social development class is often of particular interest and importance (Yao 1999). It was originally conceptualized that the transfer of virtual water would be from water-rich nations to water-scarce nations (Allan 1998). Because lesser developed nations often have the least infrastructure for storing water and distributing water, virtual water would be expected to flow from water-rich to water-scarce nations or coincidently from highly developed to less developed countries (Brown and Lall 2006). However, only a small share of inequality (19%) in internal agricultural water can be attributed to differences between social development classes (table 1). For other water uses, social development class explains large amounts of water-use inequality (53–79%) (table 1). Inequalities in external agricultural and external industrial water footprints are due to financial differences that give wealthy nations the ability to import virtual water from other countries. Inequality in internal industrial water footprints is due to technological differences that allow more highly developed countries to produce industrial products for international and intra-national markets that contain more virtual water per unit mass than industrial products produced in lesser developed nations (Chapagain and Hoekstra 2004). Inequality between classes in household use is due to differences in standard of living as well as water storage and distribution infrastructure. Because these water uses make up only a minor share of water use, most inequality is not caused by economics or differences in development status and the historic developments that created the current global pattern of development. Most of the variability in internal agricultural water use, which dominates the overall water-use inequality, can be explained by geographical factors such as climate and soil-water availability in terms of available arable land. We regressed the internal agricultural water footprint by arable land (ha per capita) and reference evapotranspiration ($mm\ d^{-1}$) in a log-quadratic functional form. This relationship explains 64% of the variance in internal agricultural water footprint. This confirms the intuitive result that variability in the internal agricultural footprint is due to the availability of arable land and a suitable climate for growing crops, not social development factors. Additional variability may be explained by the water-use efficiency of different agricultural practices (Hoekstra and Chapagain 2007, Hoekstra 2011).

4. Conclusions

Virtual water transfers can in theory result in disproportionately large populations in otherwise water-scarce countries and decrease societal resilience to drought (D'Odorico *et al* 2010). Suweis *et al* (2011) have found that 4% of international trade connections account for 80% of virtual water transfers and the increased reliance of a few hub countries for accessing virtual water under future climatic and economic scenarios. Historically, agricultural trade, a proxy for virtual water transfers, has increased exponentially with globalization but the numbers of people experiencing water shortages and the proportion of people experiencing more severe shortages have both increased considerably despite these increased transfers (Kummu *et al* 2010). Virtual water transfers are highly unequal but represent a small volume of water relative to total water needs. Water-use inequality is dominated by geographic parameters such as arable land availability and climate and not by social development status. Overall, it is unlikely that virtual water transfer will overcome these geographical constraints. This result does not preclude some countries or regions from balancing their water needs through virtual water transfers and does not exclude other positive aspects of virtual water transfers such as potentially increased food security and increased water-use efficiency at the global scale (Hoekstra 2011).

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