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ORIGINAL ARTICLE

A grid-based assessment of global water scarcity including virtual water trading

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Abstract A 0.5-degree grid-based assessment of the scarcity of global water resources including virtual water trading has been made. The three components of water availability considered for each grid were local runoff, routed flow from upstream and virtual water trading. Several assumptions were postulated to convert country-base estimations of virtual water trading to grid values. The results show that unequal spatial distribution of global water resources had been considerably neutralized by virtual water trading. A large proportion of people in the Middle-East, North-Africa and Sub-Sahara region are able to relieve their water stress through virtual water import. The paper also reports two hypothetical scenarios with extremes of natural flow availability based on the presence and absence of routed upstream flow.

Keywords Global water scarcity · Virtual water trading · Grid-based analysis · Water stress index · Spatial distribution of stress

Introduction

Global water resources in the 21st century are an increasingly important concern for the sustenance of human life, ecosystems and economic progress. The issue is a matter of international interest since the origin and movement of water is interlinked globally amongst different parts of the world; it therefore needs to be addressed in a holistic way. In this context, the availability of global water resources and its movement can be defined by the following three components; (1) Local runoff; (2) Exogenous runoff (routed runoff from upstream); and (3) Virtual Water flow.

The first two components can be considered as part of the natural movement of water. Along with its natural movement or availability, the third component of global water resources i.e. virtual water flow between countries through trading of food products is also playing an important role in global water balance. Theoretically, the total water resource available

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in the world is still enough to support the existing population, if it could be distributed homogeneously. However, in reality water resources are unevenly distributed and at current population levels many countries are already suffering from water scarcity. Direct import of water is generally out of the question, so the concept of virtual water trading has emerged. The term *Virtual Water* is defined as the amount of water needed to produce a commodity or service of any kind, although it is most commonly used in relation to the water required to produce agricultural commodities. The idea was first introduced by J.A. Allan in 1993, and later received attention by many water resources experts.

Established approaches to global water resources assessment aimed at defining annual water scarcity focus on estimating either the natural availability of water resources compared with demand, or the size of population per unit of water flow (Kulshreshtha, 1993; Raskin *et al.*, 1997; Vörösmarty *et al.*, 2000; Oki *et al.*, 2001, 2003; Alcamo *et al.*, 2003; Döll *et al.*, 2003 and Arnell, 1999b, 2004). These narrow definitions apply easily to a country or a region that has no global communications, or an isolated economy, and must achieve its development goals through its own resources. However, in the current era of globalization and abundant communication facilities, most of water-scarce countries have ample scope to compensate their shortcomings by importing food or other water-intensive products. Exchange of virtual water between different parts of the world is already playing a significant role in redressing the unequal spatial distribution of global water resources, especially in the case of countries in arid regions (Oki *et al.*, 2003).

In the present study, global estimates of virtual water trading have been superimposed on a spatially distributed grid-based analysis of global water availability. To the best of our knowledge, no other study has yet attempted to consider these two factors together, i.e. natural water availability in relation to virtual water trade at a global scale. A number of recent studies have estimated virtual water trading between countries, or between regions, including Hakimain (2003), Turton (2000), Wickelns (2001, 2004), Fadel and Maroun (2003), Yegnes-Botzer (2001), Parveen and Faisal (2004) and Yang and Zehnder (2001, 2002). Hoekstra and Hung (2002, 2004) reports the only study that estimated the global balance of virtual water trading of food and other products among different countries. These studies compared country-level virtual water trading with present water resources availability and demand by introducing indices such as *water self sufficiency* and *water dependency*, i.e. the percentage of water demand a country meets by its own resources and the percentage that it covers by importing virtual water. However, these studies did not combine virtual water trading with that of natural availability of flow explicitly in a spatially distributed manner. Basic country-based data on natural water availability was not estimated directly but collected from secondary sources as FAO (2004).

In our study, the global estimate of natural water availability has been made directly from 11 Land Surface Models (LSM), under Global Soil Wetness Project-2 (GSWP-2). The superiority of direct grid-based estimates over country-based studies has been recognized, since it can better describe the spatial variability in water resources availability. Some of the contemporary studies on global water resources availability thus concentrated on smaller scales such as basin- or sub-basin scale, or on grid-based studies. The state-of-the art approaches for these studies use a Macro-Scale Hydrological Model (MSHM) to estimate water balance components, as in the cases of Macro-PDM by Arnell (1999a,b, 2004), Variable Infiltration Capacity (VIC) model by Nijssen *et al.* (2001), Water Balance Model (WBM) by Vorosmarty (2000), and WaterGAP-2 by Alcamo (2003) and Döll *et al.* (2003). It is true that MSHMs are simpler than LSMs, and a calibrated MSHM can reproduce hydrographs better than an un-calibrated LSM. However, compared to MSHM, an LSM not only considers hydrological water balance, but details energy and water balances including hydrological, radiative and even plant physiological processes (Sellers *et al.*, 1986, 1996; Dickinson *et al.*, 1986, 1998). Currently available LSMs can simulate monthly river runoff quite well, provided that the precipitation and other forcing input data for the LSMs are accurate enough (Oki *et al.*, 1999). In fact, all the global circulation models (GCMs) that provide future climate projections use some kind of LSMs. So it is likely that LSMs will be also used directly for water resources projections in future GCMs to simulate the hydrological cycle (Oki *et al.*, 2001).

The method for estimating virtual water in the current study also differs from the methodology of recently published global scale studies. In estimating virtual water trading, Hoekstra (2004) used the virtual water content of the products of the exporting countries for both export and import process. However, in this study the virtual water content of a product was estimated separately for exporting and for importing countries. Usually, the crop yield in the exporting country is higher than the importing country, so the virtual water content of a product in the exporting country is less than that of the importing country. Differences in water contents of the product between the exporting and importing countries should be of interest to estimate how much water the importing country is saving by importing that product. So, when estimating the grid-based water balance between natural flow availability and virtual water trading, it is more realistic to consider the virtual water content of products separately for importing and exporting countries.

Virtual water trading in a broad sense includes both food products as well as many other industrial products that require water in their production process. It is thus a limitation of the study that it considered only the food products, i.e. some major crops and livestock. However, as an attempt to couple virtual water trading with natural availability of flow in a spatially distributed manner, the study still provides a useful estimate of water scarcity around the world.

Global water availability estimation

Local runoff

One of the main objectives of the second phase of the Global Soil Wetness Project (GSWP-2) was to produce the best estimate of global water cycle components for the years from 1986 through 1995. Global distribution of runoff is one of the datasets GSWP2 is producing, which is used in this study to evaluate global water scarcity. Offline simulation of the energy and water balance at the land surface was calculated by 11 LSMs for the purposes. Detailed descriptions of the project are available at Dirmeyer *et al.* (2006).

The runoff dataset produced by the first Global Soil Wetness Project, GSWP1 was evaluated by Oki *et al.* (1999). Their study pointed out that it tends to underestimate stream flow, especially in northern mid- to high-latitude, probably due to gauge under-catch in strong wind conditions. Overcoming the problem is one of the motivations of GSWP2. An empirical technique to correct gauge under-catch was proposed and adopted in the process of producing GSWP2 precipitation data. To examine the reliability of the GSWP2 Baseline (B0) results, the average LSM output of annual runoff was compared with other estimates as shown in Table 1.

It has been evident from the results that GSWP2 B0 runoff data produced by 11 GSWP2 participating LSMs are much higher than earlier studies, especially in the northern mid- to high-latitude. This is a completely opposite result from GSWP1. It might be due to the over-correction of the gauge under-catch of GSWP2 B0 precipitation dataset. An alternative approach was adopted in this case to improve the average output by excluding those extreme

Table 1 Continental runoff (km^3/year)

Region	Raskin *et al.* (1997)	Vörösmarty *et al.* (2000)	GSWP1	GSWP2-B0	GSWP2-B0-CT
Africa	4050	4520	3616	4473	4533
Asia	13510	13700	9385	15902	10797
Europe	2900	2770	2191	9827	5093
Oceania	2404	714	1680	1943	1879
North America	7890	5890	3824	10713	6456
South America	12030	11700	8789	9799	10183
Total	42784	39394	29485	52657	38941

values for each grid out of 12 models, i.e. the maximum and minimum values of two models. This version of GSWP2 output was named as GSWP2-B0-CT. Even though such a measure has no strong scientific rationalale, still it improved the runoff estimates significantly as shown in Table 1. The only problem that remains is in data for Europe, which are still very high. It is assumed that possibly the original precipitation data in the corresponding European region had already corrected for wind under catch, and the GSWP-2 forcing data in the region was over-corrected. Further improvement of the issue is under consideration. In this study we used the output from the GSWP2-B0-CT version for local runoff estimate.

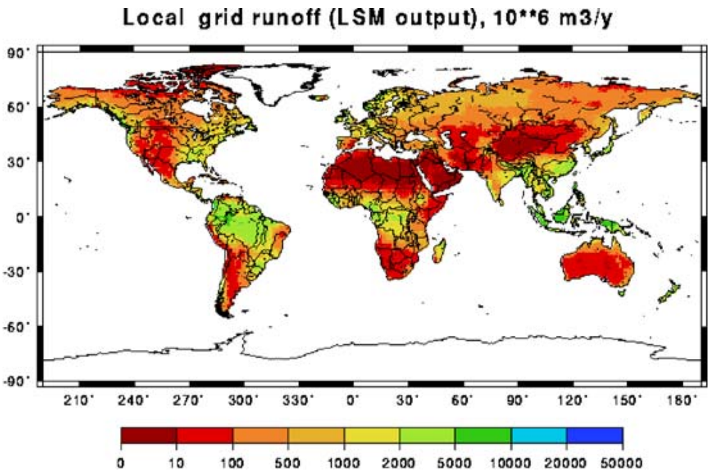
Exogenous runoff from upstream

Present output from the GSWP2-B0-CT version can be further routed to global river networks to produce estimates of the river discharge. Total Runoff Integrated Pathways (TRIP), developed by Oki and Sud (1998), was used for this purpose at a resolution of 0.5×0.5 degree grids. A detailed description of the TRIP model is available at Oki *et al.* (1999) or Okada (2000). Actually, the grid runoff estimated from those LSMs is the *local runoff* as shown in Figure 1a. Use of a river routing model TRIP added the *exogenous runoff* available at each grid from upstream to that of local runoff. The difference between TRIP-routed runoff with that of LSM runoff is actually the net contribution to a cell of exogenous runoff from the upstream as shown in Figure 1b.

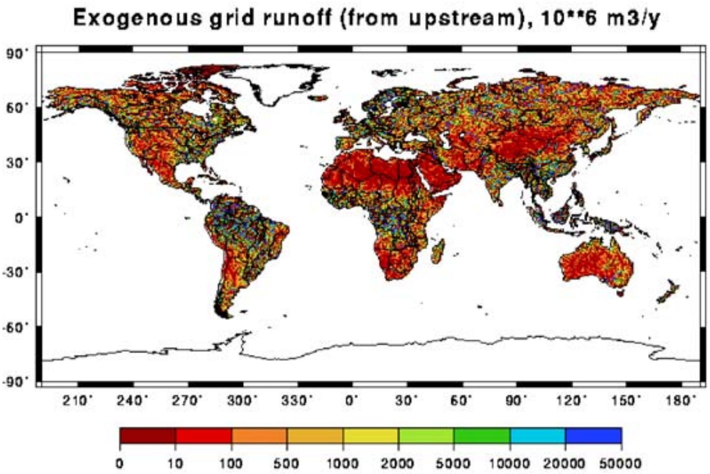
Theoretically, all of this exogenous runoff should be available at the downstream grid points, as assumed in previous studies by Vörösmarty *et al.* (2000) and Alcamo *et al.* (2003). However, in reality because of upstream withdrawal, a significant portion of this exogenous runoff is not available at the downstream grids. Especially in the case of long trans-boundary rivers, in arid or semiarid regions, the problem is more serious. This exogenous runoff is actually an uncertain amount of water for a particular grid. This study thus critically assessed the routed amount of flow and accounted for the effect by introducing the following formula:

$$Q = R + \alpha \sum D_{\text{up}}$$

where, Q is the water available at a particular grid, R is the grid runoff from the LSM output, D is the discharge from other upstream grids due to routing, α is the ratio of water from outside the grid to that of the water resources inside the grid. Here $\alpha = 1.0$, means that all of the exogenous runoff generated upstream from the routing scheme can be used at the downstream grid, i.e. the TRIP-routed discharge. When $\alpha = 0.0$, it assumes that no upstream contribution



(a)



(b)

Fig. 1 Global distribution of runoff (a) local runoff or vertical component of flow (direct output of runoff from LSMs without routing) (b) Exogenous or horizontal component of flow (net upstream contribution of flow due to routing effect)

is available, so the water resources availability at a grid is just what it is available within the grid, i.e. only the local runoff. Depending on a number of factors as climatic, socio-economic, land use, or topographical factors that affect upstream water withdrawal, the α value varies among different regions in the world.

Estimating virtual water exchanges

Unit requirement of water resources to produce each commodity (hereafter called *UW*) is the starting point for the quantification of virtual water trading. Some estimates of *UW* are available from Wichelns (2001), Hoekstra and Hung (2002), and Oki *et al.* (2003). However, there are still a lot of uncertainties in determining *UW*, probably because alternative rational

Table 2 Estimated values of UW for different products by Oki *et al.* (2003)

Products	Unit Water Content, UW (m^3/ton)
Rice	3200
Wheat	1600
Maize	900
Soybean	2500
Barley	1200
Chicken	4500
Pork	5900
Beef	20700
Egg	3200
Milk	560

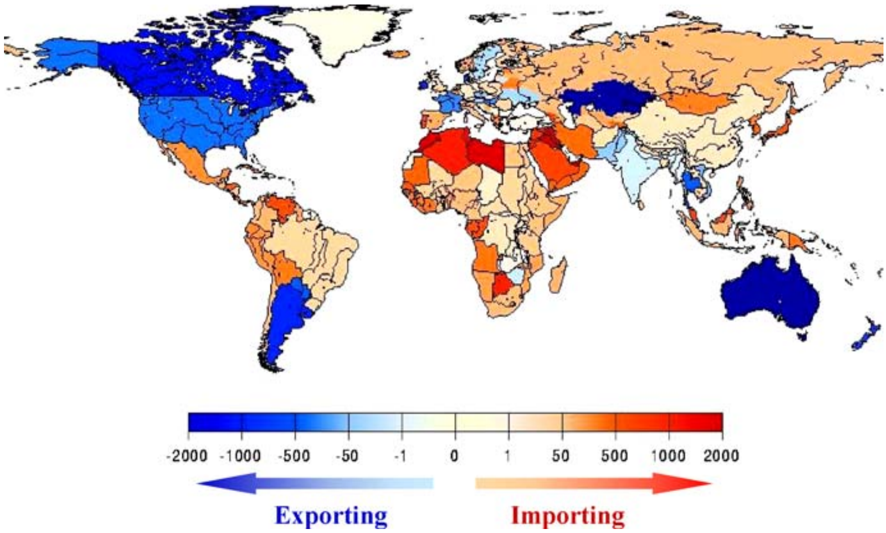


Fig. 2 Net trading of virtual water among the countries ($m^3/c/y$)

definitions of virtual water have been made. Previous studies have estimated *UW* for grains, and livestock individually as described detail in the reference Oki *et al.* (2004). *UW* estimates for individual products were made based on the available information or experience in Japan. A list of estimated UW for different products is shown in Table 2.

As mentioned above, Oki *et al.* (2003) differentiated *virtual water content* of a product for both the exporting and importing countries. Usually it varies due to the difference in crop yields between the two respective countries. FAO data sets of crop yields for different countries in the world (FAO, 2000) were used to estimate the UW requirements of products for each country, and compared to Standard UW estimates and crop yield. The modified UW requirement is then termed the virtual water content of a product for that country. FAO estimates of global trading of crops and livestock between different countries for the year 2000 (FAO, 2004) were utilized to estimate the country-level annual virtual water flows between countries. To make the figure comparable among different countries, the total amount of export and import was divided by year 2000 population and the country-based per capita export or import is shown in Figure 2.

Table 3 Comparison of food consumption rate among rural and urban people (modified from Regmi and Dyck, 2001)

	Urban				Rural			
	Cereals	Roots & tubers	Fruit & vegetables	Meats & offals	Cereals	Roots & tubers	Fruit & vegetables	Meats & offals
				Kg/capita/year				
China[a]								
1988	199	NA	195	29	208	NA	135	12
1998	140	NA	166	30	200	NA	128	16
				Grams/capita/week				
Indonesia[b]								
1978	2.165	275	1.005	64	2.560	810	975	36
1987	2.182	279	1.275	108	2.579	612	1.364	16
				Kg/capita/month				
Pakistan[b]								
1979	10.59	0.73	NA	0.85	13.66	0.72	NA	0.46
1987/88	9.75	0.68	NA	0.76	12.69	0.68	NA	0.51

[a]Economic Research Service, USDA
[b]FAO, 1993

Because, FAO estimates for crop trading were available at country level only, virtual water trading was estimated at country scale. This is a usual procedure followed by other global scale studies as well (Hoekstra and Hung, 2002, 2004; Oki *et al.*, 2003). However, this study assumes that virtual water export and import should have specific spatial variability within the country based on the nature of land use and population density. The first scientific question was how to match these country level estimates of virtual water trading to that of the grid runoff values from GSWP2.

In this connection, the following assumptions were made:

- virtual water export from a country is spatially distributed among the grids in proportion to the density of agricultural areas.
- virtual water import by a country is distributed to its grids in proportion to population density.

In the case of virtual water export, it can be reasonably assumed that crops or livestock are collected from those agricultural areas utilizing local water resources. Therefore the virtual water export for a particular grid can be estimated as:

$$= (\text{Agricultural area of the grid}/\text{Total Agricultural area of the country}) \\ \quad * \text{Total amount of virtual water exported from the country}$$

In the case of the country-based virtual water import value, however, allocations among grids are not so simple. For a particular country, there are at least two questions that need to be answered as follows – whether there is any significant difference in food consumption patterns amongst different parts of the country, and which parts of the country depend heavily on imported foods. As shown in Table 3, the per capita food consumption among urban and rural areas actually does not differ much (Regmi and Dyck, 2001). The only difference is the combination of foods as cereal, meat or vegetables. Converting the total food consumption into equivalent virtual water content, the difference is again negligible. Another study by Ozcan (2003) on food consumption patterns in Turkey reported the same results.

Regarding the other issue – i.e. the dependence in different parts of a country (e.g. urban and rural) on imported food products – the most important problem is the extent of internal trading, data on which are rarely available, and vary significantly among countries. It is rational to assume that urban people are mostly dependent on imported food products, while the rural people mostly produce their own food. However, other factors such as storage facilities, economic conditions and food habits, etc. may significantly affect dependence on imported food. For a 0.5-degree grid-based analysis, in the absence of adequate information, such factors are difficult to quantify accurately. Under the same program, studies are in progress to consider such effects in as much detail as possible. At this stage of the present study, we assumed simplistically that all the imported food products for a particular country are equally distributed along different grids based on population density. Based on the above assumptions, the grid based distribution of virtual water exports and imports is shown in Figure 3a and b.

Water stress level

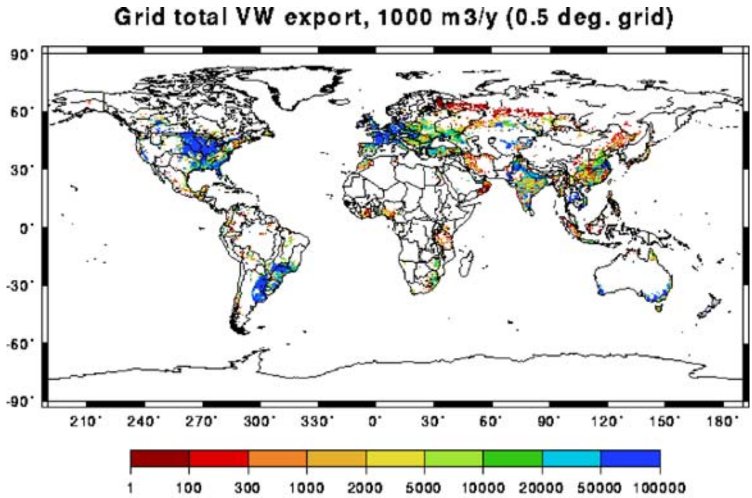
There are a number of indices used to define water resources stress. Two of the widely used indices are the *use- to- resources ratio* and *per capita water availability*. The ratio of water use, or withdrawal, to runoff was used as an indicator in many studies such as in the UN Comprehensive Assessment of the Freshwater Resources by Raskin *et al.* (1997), and in Alcamo *et al.* (2003); Vorosmarty *et al.* (2000), Oki *et al.* (2001), and Arnell (1999b). However, the difficulty with this indicator is correctly estimating water use. Another index developed by Falkenmark *et al.* (1989) is simpler, and defines water stress by estimating the number of people per flow unit (i.e. 10^6 m^3) annually. It differentiates four stress levels based on per capita water availability as follows:

Per capita water availability (m^3/c/y)	Stress level
>1700	No stress
1000–1700	Moderate stress
500–1000	High stress
<500	Extreme stress

Several studies designed for global water resources assessment (Arnell, 2004; Revenga *et al.*, 2000; Kulshreshtha, 1993) also adopted this index.

In the present study, the Falkenmark index was adopted because it is simple and comprehensive to couple with virtual water export and import values. The per capita virtual water exports from different grids in the exporting country were deduced from the per capita runoff availability in those grids. Likewise, per capita virtual water import was added to the per capita annual runoff availability in the importing country grids. The above four stress levels were adopted and the number of people under each stress level estimated. To differentiate the effect of virtual water trading on relieving stress, two estimates were made: one for water stress using the GSWP2 results without virtual water trading; and the other for GSWP-2 results combined with the net virtual water trade.

One other important concern is the exogenous runoff availability. As mentioned in the previous section, this flow is actually uncertain so that a coefficient α was introduced. Here, two extreme scenarios of α value have been considered as $\alpha = 1.0$, i.e. full availability



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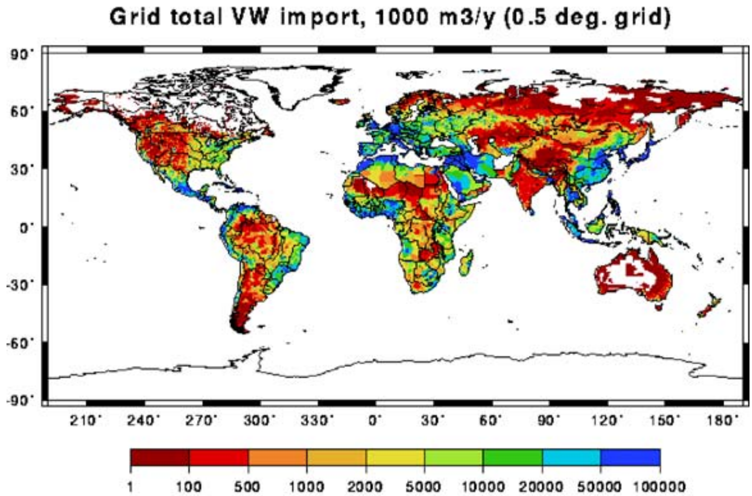


(b)

Fig. 3 Distribution of country-based virtual water trading among grids; (**a**) Export of virtual water (based on real water requirements of the country) (**b**) Import of virtual water

of routed flow from upstream grids; and $\alpha = 0.0$, i.e. no upstream flow available at those downstream grids but only the LSM grid runoff. Availability of this exogenous flow in the real world would be between these two α values.

Global figures

Table 4, shows detailed results of the number of people at different stress levels under different scenarios. Population data used for this purpose are derived from the CIESIN 2.5-minute grid data aggregated to 0.5 degree. Because of differences in the land-sea mask between CIESIN and GSWP2 grids, special adjustments were made to relocate CIESIN

Table 4 Global population under different stress levels and scenarios, including virtual/real water flows and exogenous runoff

	$\alpha = 1.0$ Stress level (m^3/c/y)		$\alpha = 0.0$ Stress level (m^3/c/y)	
	Without VW	With VW	Without VW	With VW
Global population in millions				
No stress: >1700	3768	3931	2179	2347
Moderate: 1000–1700	524	564	756	879
High: 500–1000	632	705	996	1103
Extreme: <500	1142	851	2111	1672
Population below 1000 m^3/c/y level	1774	1556	3107	2775
Population below 1700 m^3/c/y level	2298	2120	3863	3654
Virtual water trading derived from				
–Increase in per capita water availability	4160		4160	
–Decrease in per capita water availability	1525		1525	

grids to match the GSWP2 grids. Population data for boundary grids between two countries also needed adjustment when aggregated from 2.5-minute to 0.5-degree grids. However, both the cases of difference in land-sea mask and country boundaries, still some problems remain so that minor deviation in population count for smaller countries might occur. Further improvement of the problem by adjusting GSWP2 and CIESIN boundaries is underway in future studies.

It can be seen from Table 4 that virtual water trading plays an important role in relieving pressure for a large number of global population. The maximum number of people that reduced their stress are in the group with the extreme stress level of 500 m^3/c/y. Arid countries with very low water availability belong to this group as they have no option but to survive by importing water-intensive products. Gradually, for reduced stress levels, such imports of virtual water declined. However, for the 1000 m^3/c/y or 1700 m^3/c/y categories, the total number of people relieved from stress through virtual water trading is still significant. As shown at the bottom of Table 4, the number of people benefiting from an increase in per capita water availability due to virtual water trading is higher than the number of people suffered from a reduction in per capita water availability.

Table 4 shows the difference in water availability under two extreme α values. The exact value of α is difficult to estimate and varies between different regions. Here $\alpha = 1.0$ is the best scenario when all the upstream flow is available for downstream users. However, in the changing world with increasing population and industrial activities, it is already evident that the upstream water withdrawal rates are increasing gradually, thus decreasing the value of α over time. For trans-boundary rivers, a decreasing trend in α might portend increasing conflict over water sharing between countries. So, the $\alpha = 0.0$ figure can be seen as the worst scenario at some hypothetical future time.

Regional figures

The spatial distribution of water stress levels affected by virtual water trading on a regional basis can be seen in Figures 4 and 5. These Figures indicate that countries in the Middle-East and North-African are relieving their water stress significantly by importing virtual water. To explore this phenomenon further, Table 5 shows a quantitative analysis based on six different regions. On the top of the list, the North-Africa and Middle-East countries benefit the most

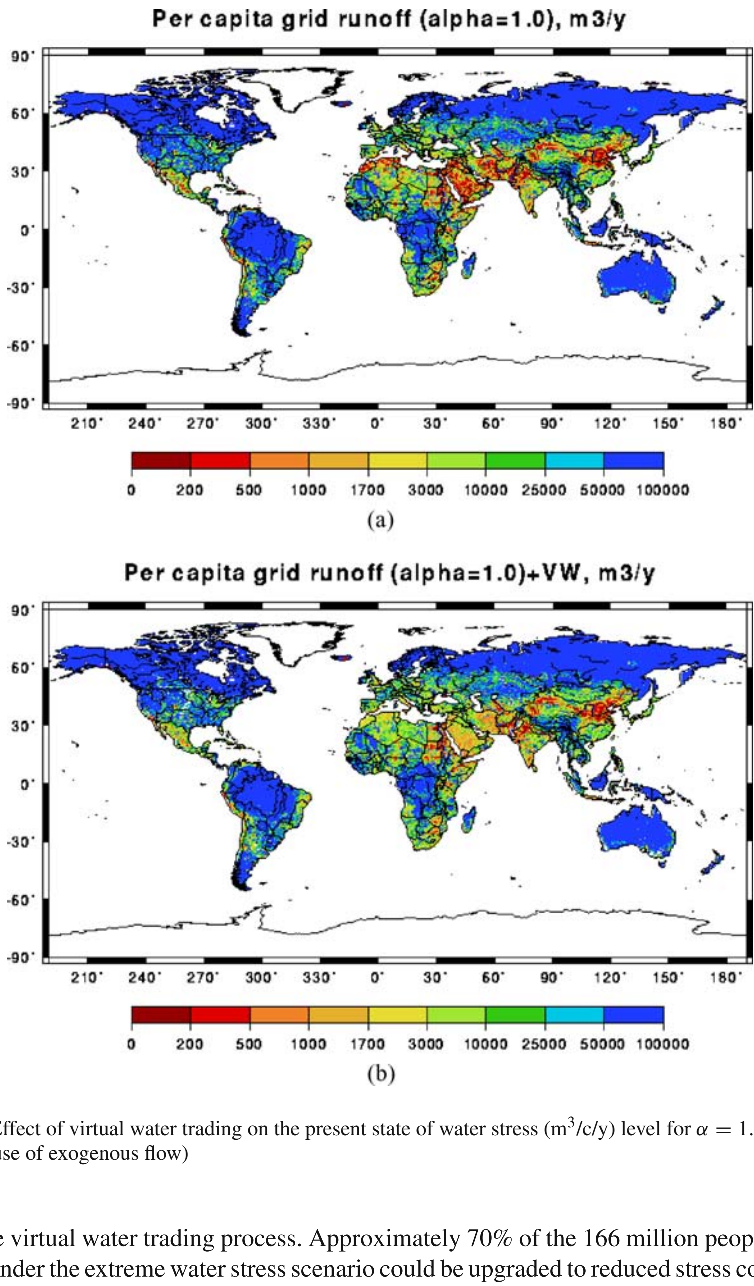
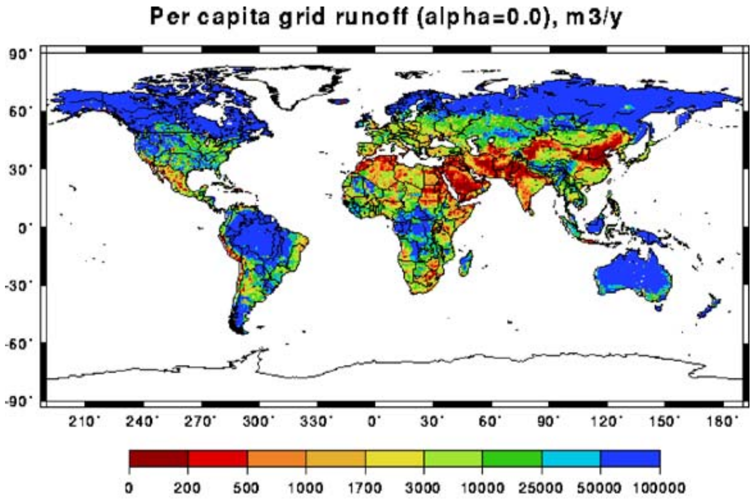
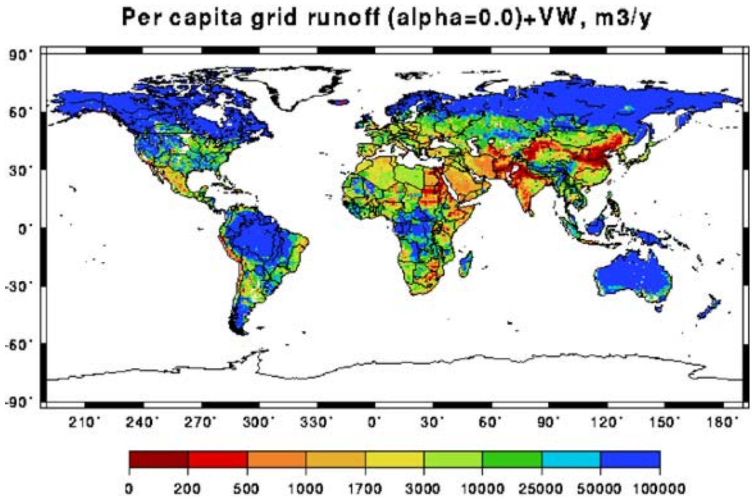


Fig. 4 Effect of virtual water trading on the present state of water stress (m^3/c/y) level for $\alpha = 1.0$ scenario (i.e. full use of exogenous flow)

from the virtual water trading process. Approximately 70% of the 166 million people of this region under the extreme water stress scenario could be upgraded to reduced stress conditions through virtual water trading. In total almost 90% of the population could increase their per capita water availability in the region through virtual water trading. Next to this region is Latin America, which also improved per capita water availability through virtual water trading. For Asia the net upgrading of per capita water availability is the lowest. This result is to some extent confusing considering the country-based data shown in Figure 2, which shows that most of Asian countries are importing virtual water. Because of the larger import of virtual water, the per capita water availability should increase for a larger number of people.



(a)



(b)

Fig. 5 Effect of virtual water trading on the present state of water stress (m^3/c/y) level for $\alpha = 0.0$ scenario (i.e. no exogenous flow)

However, this actually happened because of the fact that most Asian people live in rural areas or agricultural districts. Therefore the export of virtual water from those agricultural grids affected a large number of people in the form of reduced per capita water availability. On the other hand, even though the OECD countries are larger exporters, the population density in their agricultural grids are lower than Asian countries, so that the percentage of people suffering from reduced per capita water availability is comparatively lower than Asian countries.

Regarding the effect of exogenous runoff, the region FSU is affected most seriously for the case where $\alpha = 0$. This is because of the large number of long rivers in the FSU region where

Table 5 Regional disaggregation of water stress affected by virtual water (VW) trading and exogenous flow

Stress level (m3/c/y)	Population (million)					
	Asia	FSU	Latin America	N. Africa & Mid. East	OECD	SubSahara
			$\alpha = 0.0$, without VW			
<500	1346.79	72.7830	132.960	242.080	149.876	153.552
500–1000	596.735	40.4396	65.3456	46.6223	148.526	86.4631
1000–1700	404.240	33.5412	50.6976	28.2680	135.057	94.6533
>1700	833.344	140.632	246.496	51.9847	520.554	328.044
			$\alpha = 0.0$, with VW			
<500	1260.48	47.7393	84.7941	80.4676	96.3944	101.258
500–1000	589.564	55.8949	87.2469	77.9914	151.068	127.415
1000–1700	437.615	38.7019	58.4312	79.2682	151.965	96.2663
>1700	843.970	143.938	261.603	149.346	544.242	343.043
			$\alpha = 1.0$, without VW			
<500	681.028	15.0467	107.178	166.351	71.5279	88.3487
500–1000	394.449	25.0310	27.8109	41.0389	69.2100	66.2937
1000–1700	294.123	22.3815	37.4982	29.2238	81.0784	53.9800
>1700	1812.41	225.031	323.184	150.061	732.252	458.195
			$\alpha = 1.0$, with VW			
<500	637.054	10.07678	60.3195	49.7634	30.2300	62.7386
500–1000	383.744	20.0299	58.1494	52.1955	98.2730	80.1350
1000–1700	320.609	30.2506	34.7646	49.2471	60.8454	57.8338
>1700	1829.93	226.673	340.330	235.935	762.129	467.448
			Total			
Increase in per capita water availability	1868.29	206.110	408.677	345.076	665.238	580.066
Decrease in per capita water availability	1178.82	33.9605	44.0391	17.0300	238.578	8.47740

the routing effect therefore produces a large percentage of flow which is affected in the case where $\alpha = 0$. In practice the α value should vary within 0 to 1 so that the tabulated numbers here provide a complete range of future possibilities of the exogenous runoff availability in different parts of the world.

Conclusion

This study demonstrated a state-of-the art approach of preparing a grid-based estimation of virtual water trading in different parts of the world, coupled with the latest estimation of runoff availability from the GSWP2 project. The percentage of population that benefited from virtual water trading is the highest for the Middle East, North African, and Sub-Saharan African regions. Considering the Falkenmark index, the population below the worst stress scenario, i.e. 500 m^3/c/y water availability, are the greatest beneficiaries of this virtual water trading. Around 25% of the total global population suffering at this acute shortage level could upgrade themselves to the upper level.

The difference in the number of affected people for country-level and grid-level studies is another important finding to note here. From the country-based estimates it was seen that some OECD countries including USA, Canada, Australia, and New Zealand are the largest exporters of virtual water, and Asia is the greatest net importer. However, the regional estimate of affected population based on grid-base calculations shows that the percentage of people suffering from a reduction in per capita water availability due to export of virtual water is still higher for Asia compared to that of OECD countries. This is because of the difference in the spatial distribution of land use and population density among different regions.

Because of the upstream water withdrawal effect, availability of the routed runoff is actually quite uncertain, so two different scenarios of natural runoff, as with or without routed flow, were made. This analysis showed that the global population under the 500 m^3/c/y stress level would be doubled under the worst scenario of non-availability of upstream routed flow. In the changing world with increased population and water demand, conflicts on water sharing issues along the trans-boundary rivers are already evident in many parts of the world, and these might be aggravated in future.

The main limitation of the study is that the estimated grid values of virtual water trading are based on country-level estimations of virtual water trading from the FAO food trading data base, modified by some assumptions. True grid-based estimates of virtual water trading would require a direct estimation of virtual water flows among different grids, irrespective of national boundaries between countries. Unfortunately such detailed information is not available on a global scale; nevertheless, the output of this study can be considered useful as an improved and more realistic analysis of global water scarcity incorporating virtual water trading.

References

Alcamo J, Doll P, Heinrichs T, Kaspar F, Lehner B, R.osch T, Siebert S (2003) Global estimates of water withdrawals and availability under current and future business-as-usual conditions. Hydrol Sci J 48:339–348

Allan JA (1998) Moving water to satisfy uneven global needs: trading water as an alternative to engineering it. ICID J 47(2):1–8

Allan JA (2003) Virtual water – the water, food, and trade nexus: useful concept or misleading metaphor? Water Int 28(1):106–113

Allan JA (1998) Virtual water: a strategic resource. Global solutions to regional deficits. Ground Water 36(4):545–546

Allan JA (2002) The Middle East Water Question: Hydropolitics and the Global Economy. L.B. Tauris Publishers, London

Arnell NW (1999a) A simple water balance model for the simulation of streamflow over a large geographic domain. J Hydrol 217:314–335

Arnell NW (1999b) Climate change and global water resources. Global Environmental Change 9:31–49

Arnell NW (2004) Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change 14:31–52

Center for International Earth Science Information Network (CIESIN) (2000) Columbia University; International Food Policy Research Institute (IFPRI); and World Resources Institute (WRI) (2000) Gridded Population of the World (GPW) Version 2. CIESIN, Columbia University, Palisades, NY, available at http://sedac.ciesin.columbia.edu/plue/gpw

Dickinson RE, Henderson-Sellers A, Kennedy PJ, Wilson MF (1986) Biosphere – atmosphere transfer scheme (BATS) for the NCAR community climate model. Tech. Report no. TN275+STR, National Center for Atmospheric Research, Boulder, Colorado, USA

Dickinson RE, Shaikh M, Bryant R, Graumlich L (1998) Interactive canopies for a climate model. J Climate 11:2823–2836

Dirmeyer PA, Gao X, Zhao M, Guo Z, Oki T, Hanasaki N (2006) GSWP2 multimodel analysis and implications for our perception of the land surface. Bulletin of the American Meteorological Society 87(10):1381–1397

Döll P, Frank K, Bernhard L (2003) A global hydrological model for deriving water availability indicators: model tuning and validation. J Hydrol 270:105–134

El Fadel M, Maroun R (2003) The concept of ‘virtual water’ and its applicability in Lebanon. In: Hoekstra AY (ed) VirtualWater Trade: Proceedings of the International Expert Meeting on VirtualWater Trade, Research Report Series No 12. IHE Delft, The Netherlands

FAO (2004) Online AQUASTAT 2000 database
Falkenmark M, Lundquist J, Widstrand C (1989) Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. Natural Resources Forum 13:258–267
Hakimain H (2003) Water scarcity and food imports: an empirical investigation of the "virtual water" hypothesis in the MENA region. Review of Middle East Economics and Finance 1(1):71–85
Hoekstra AY, Hung PQ (2002) Virtual Water Trade: A Quantification of Virtual Water Flows between Nations in relation to International Crop Trade, Value of Water. Research Report Series 11, IHE Delft, The Netherlands
Hoekstra AY, Hung PQ (2004) Globalisation of water resources: international virtual water flows in relation to crop trade. Global Environmental Change Part A 15(1):45–56
Kulshreshtha SN (1993) World Water Resources and Regional Vulnerability: Impact of future Changes, IIASA Research Report RR-93-010, June 1993, pp 137
Okada Y (2000) Simulating discharge of major rivers in the world through development of a global river channel network at 0.5 resolution. Master's thesis, University of Tokyo, Tokyo, Japan
Oki T, Agata Y, Kanae S, Saruhashi T, Yang D, Musiake K (2001) Global assessment of current water resources using total runoff integrating pathways. Hydrol. Sci. J. 46:983–996
Oki T, Sud YC (1998) Design of Total Runoff Integrating Pathways (TRIP) – A global river channel network. Earth Interactions 2 (http://EarthInteractions.org)
Oki T, Nishimura T, Dirmeyer P (1999) Assessment of land surface models by runoff in major river basins of the globe using Total Runoff Integrating Pathways (TRIP). J Met Soc Jpn 77:235–255
Oki T, Sato M, Kawamura A, Miyake M, Kanae S, Musiake K (2003) Virtual water trade to Japan and in the world. In: Hoekstra AY (ed) Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade, Research Report Series No. 12. IHE Delft, The Netherlands
Ozcan KM (2003) Basic food consumption in Turkey: effects of income, price and family size in Urban areas, occasional paper available at www.bilkent.edu.tr/~kivilcim/foodpaper.pdf
Nijssen B, Greg M, O'Donnell AF, Dennis P (2001) Hydrological sensitivity of global rivers to climate change. Climatic Change 50:143–175
Parveen S, Faisal IM (2004) Trading virtual water between Bangladesh and India: a Politico – economic dilemma. Water Policy 6:1–10
Raskin P, Gleick P, Kirshen P, Pontius G, Strzepek K (1997) Comprehensive Assessment of the Freshwater Resources of the World. Stockholm Environment Institute, Stockholm
Regmi A, Dyck J (2001) Effects of urbanization on global food demand changing structure of global food consumption and trade. In: Regmi A (ed) Market and Trade Economics Division, Economic Research Service, U.S. Department of Agriculture, Agriculture and Trade Report, WRS-01-1.
Revenga C, Brunner J, Henninger N, Kassem K, Payne N (2000) Pilot analysis of global ecosystems: freshwater ecosystems. World Resources Institute and Worldwatch Institute, Washington, DC
Sellers PJ, Mintz Y, Sud YC, Dalcher A (1986) A simple biosphere model (SiB) for use within general circulation models. J Atmos Sci 43:505–531
Sellers PJ, Randall DA, Collatz GJ, Berry JA, Field CB, Dazlich DA, Zhang C, Collelo GD, Bounoua L (1996) A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: model formulation. J Climate 9:676–705
Turton AR (1999) Precipitation, people, pipelines and power: towards a 'virtual water' based political ecology discourse. MEWREW Occasional Paper No. 11, Available at http://www.soas.ac.uk/waterissues/occasionalpapers/OCC11.PDF
Vorosmartsy C, Green P, Salisbury J, Lammers R (2000) Global water resources: vulnerability from climate change and population growth. Science 289:284–288
Wichelns D (2001) The role of 'virtual water' in efforts to achieve food security and other national goals, with an example from Egypt. Agric Water Manage 49:131–151
Yang H, Zehnder AJB (2002) Water scarcity and food import: a case study for Southern Mediterranean Countries. World Development 30(8):1413–1430
Yang H, Zehnder A (2001) China's regional water scarcity and implications for grain supply and trade. Environ Plan A 33:79–95
Yegnes-Botzer A (2001) Virtual water export from Israel: quantities, driving forces and consequences. M.Sc. Thesis, DEW 166, IHE, Delft, The Netherlands