EE80S Lab Packages

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Lab 2: Refining the Problem - Measuring Carbon Footprints

Activity Goals

- Understand the impacts of your consumption habits on carbon cycle relative to average US and global citizens.
- Design process - Refining the problem. Examine how the metrics one uses to examine a problem can impact proposed solutions to that problem; unpack information gathering approaches; work through conflicting or black-boxed data
- Communicative: Practice defending your findings to other groups and participants

Background Information

Image from bayouwoman.wordpress.com

The historian Lewis Mumford noted that “carboniferous capitalism” relies on the “accumulated wealth” of carbon based energy that took millennia to establish. The fossil fuels we rely on today are the products of long ecological and geological processes, and our use diminishes a stock of finite resources. He distinguished carboniferous capitalism from other era(s) where human civilization acquired flows of energy from the sun, mainly from wood biomass and agriculture. Mumford argued that carboniferous capitalism’s “habituation to wreckage and debris” with “disregard for a balanced mode of production and consumption” would strip human civilization of the energy resources upon which it is built.

We now know there are other problems with a fossil fuel based global economy. In additional to the declines in carbon based energy stocks, we recognize that adding carbon to the atmosphere is inducing changes to the planet’s climate. The greenhouse effect is the result of increased levels of gases like carbon dioxide, methane, and nitrous oxide that trap incoming energy from the sun into the atmosphere. While the effect was first widely publicized by the Swedish scientist Arrhenius in the late 1800s, it is only with rigorous scientific evidence from air samples to ice cores that the effect has become widely accepted. Switching from carbon-based energy stocks (coal, petroleum, natural gas) to renewable flows of energy is now seen as one of human civilization's most pressing challenges.

Many human activities are associated with the carbon-based economy. Noting the figure below you will see that the relative greenhouse gas (GHG) contribution of individuals from the industrialized nations (the OECD, or G20), are much larger than developing countries (see the balloons for India and China). The US has a particularly large average per capita carbon footprint, but this says very little about the differences that might exist between different individuals, the rich and poor in each country, those with different cultural values, etc.

Image from www.internationalrivers.org.

While national-level GHG inventories may be important for developing national policies for carbon and renewable energy, GHG inventories of individuals give everyone an opportunity to know their relative contribution and perhaps act on that information.

A carbon footprint is essentially a net GHG inventory for an individual. It looks at an individual’s or household’s role in contributing to GHG emissions. It looks the various individual behaviors—commuting, heating and lighting a home, using appliances, etc.—and estimates the relative GHG contribution of each, and aggregates those into a total carbon footprint.

In this lab you will explore several online carbon footprint calculators. We want you to think about what they are asking, how are they compiling your behavioral information, what kinds of assumptions are they making, and how accurately their data collection methodology captures the carbon impact of your actions. Read the lab exercise instructions below.

Pre-Lab Homework

*** For this lab to work, the following steps 1 through 6 need to be done BEFORE the meeting for Lab 2. Failure to complete the pre-lab homework will result in you receiving NO CREDIT for this lab.**

Your group will be assigned three of the following carbon calculators:

1) Nature Conservancy's Carbon Footprint Calculator
http://www.nature.org/initiatives/climatechange/calculator/

2) Terrapass: http://terrapass.com/carbon-footprint-calculator/

3) UC Berkeley Institute of the Environment CoolClimate Carbon Footprint Calculator
http://coolclimate.berkeley.edu/

4) www.carbonfootprint.com/calculator.aspx

5) EPA Greenhouse Gas Household Emissions Calculator
http://www.epa.gov/climatechange/emissions/ind_calculator.html

6) Yahoo! Green Carbon Footprint Calculator
http://green.yahoo.com/calculator/

NOTE -- For each of the following steps, results for all group members should be entered in the same document. Coordinate how you will do this (Google Docs is probably the easiest way to do it, but you can use e-mail, etc. if your group prefers). Link to Document with Tables: **Lab 2 Tables.doc**

1. Before the lab 2 meeting each individual in your group should independently follow the directions given for each of the three assigned carbon calculators to calculate their personal carbon footprint. Make sure you normalize the numbers so they are in comparable units by converting to tons of Co2 and to an individual (not a household), as necessary. Each group member should enter your own carbon footprint results for each of the three calculators you used in **Table 1** in the attached document.

2. Hypothetically try to reduce your carbon footprint by 20% (forgoing carbon consumption every 5th time; not a dramatic reduction). What would you first try to change about your consumption or behaviors? Which question might you answer differently to reduce the footprint?

3. In **Table 2** in the attached document, write down a few sentences about the change you personally decided to make, and how you decided on that choice. Think about the values and assumptions embedded in your choice. What ideas from the readings in this class, in other classes or from your prior experience are informing your choice? What further information could help you to make this choice?

4. After completing **Table 2**, recalculate your footprint using the three carbon calculators with this change in mind. (Don't worry about over estimating or underestimating what you could modify, just use your instinct and recalculate once.) Enter your numbers in **Table 3**.

5. Upload your group's completed document to the lab website or bring it to lab, as directed by your instructor.

6. Think about and be prepared to discuss the following questions: How did your individual numbers compare for the different calculators? Did you get the same results for each? What do think contributed to differences, if there were any?

In Lab Meeting:

Group Presentations

With your group, organize a 3-5 minute presentation to the class. Compare the criteria used by different carbon footprint calculators and the different impact that particular lifestyle changes had in different calculators. Here are the questions we want you to answer. Use powerpoint to prepare a presentation that you can show to the class.

Use the following questions as guidelines for organizing your presentation. However, try to be creative - we are trying to avoid a prescriptive exercise.

Presentation Part A : Examining the carbon calculators as technologies

- Why are the numbers from each calculator, both before and after each change, different? (Think of these calculators as technologies. Are they designed differently?)
- What did you learn about the design of these different carbon calculators by comparing results from different calculators for different members of your group?
- What tradeoffs do designers of this technology make in designing their particular carbon footprint calculators (e.g., user friendly v. complexity, targeted vs. comprehensive)?
- Talk about the differential impacts of behavioral changes among the different calculators. Why do you think some behavioral changes had a bigger impact according to some calculators than others? What aspects of the calculator designs are responsible for these differences? What implicit assumptions or explicit design criteria are behind these design differences?
- How transparent is the technology itself? Where are these numbers coming from? Do some calculators provide information that makes it easier to see how they produce their results than others? What implicit criteria/assumptions are missing?
- What are the different biases of the organizations sponsoring these different technologies? How do the priorties of the sponsoring organization influence the design of the carbon calculators?

Presention Part B: Which of the three calculators would you choose as the "least flawed" technology and why? State your case.

Group Discussion

- Does hearing other groups' comparisons of different calculators change your assessment of the three calculators you used? If so, why?
- What is useful to you about calculating your carbon footprint? In what ways might this assessment be limited? How do the notable differences between your carbon footprint as indicated by each calculator impact your impression of carbon calculators as a useful technology?
- We can assume that for now all these different calculators maintain equal legitimacy in the field. We might also assume that eventually one will win out (stabilize) over others and become more prominent (think Google vs. other internet search engines or the fact that LEED certification is now the running standard for green building). What are the processes involved in one gaining more influence than another? In the case of carbon calculators would this be a good thing? Why or why not?
- What might the broader impacts of one calculator becoming the dominant technology over the others have for broader sustainability efforts?

No post-lab homework this week.

Lab 2. Group Number: _______

Table 1

Carbon Calculator	Name 1 (tons CO2)	Name 2 (tons CO2)	Name 3 (tons CO2)	Name 4 (tons CO2)	Name 5 (tons CO2)

Table 2

Name	Behavior Change	Justification for Change

Table 3

Carbon Calculator	Name 1 (tons CO2)	Name 2 (tons CO2)	Name 3 (tons CO2	Name 4 (tons CO2)	Name 5 (tons CO2)

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ORIGINAL ARTICLE

Water footprints of nations: Water use by people as a function of their consumption pattern

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Abstract The water footprint shows the extent of water use in relation to consumption of people. The water footprint of a country is defined as the volume of water needed for the production of the goods and services consumed by the inhabitants of the country. The internal water footprint is the volume of water used from domestic water resources; the external water footprint is the volume of water used in other countries to produce goods and services imported and consumed by the inhabitants of the country. The study calculates the water footprint for each nation of the world for the period 1997–2001. The USA appears to have an average water footprint of 2480 m^3/cap/yr, while China has an average footprint of 700 m^3/cap/yr. The global average water footprint is 1240 m^3/cap/yr. The four major direct factors determining the water footprint of a country are: volume of consumption (related to the gross national income); consumption pattern (e.g. high versus low meat consumption); climate (growth conditions); and agricultural practice (water use efficiency).

Keywords Water footprint · Consumption · Virtual water · Indicators · Water use efficiency · External water dependency

Introduction

Databases on water use traditionally show three columns of water use: water withdrawals in the domestic, agricultural and industrial sector respectively (Gleick, 1993; Shiklomanov, 2000; FAO, 2003). A water expert being asked to assess the water demand in a particular country will generally add the water withdrawals for the different sectors of the economy. Although useful information, this does not tell much about the water actually needed by the people in the country in relation to their consumption pattern. The fact is that many goods

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consumed by the inhabitants of a country are produced in other countries, which means that it can happen that the real water demand of a population is much higher than the national water withdrawals do suggest. The reverse can be the case as well: national water withdrawals are substantial, but a large amount of the products are being exported for consumption elsewhere.

In 2002, the water footprint concept was introduced in order to have a consumption-based indicator of water use that could provide useful information in addition to the traditional production-sector-based indicators of water use (Hoekstra and Hung, 2002). The water footprint of a nation is defined as the total volume of freshwater that is used to produce the goods and services consumed by the people of the nation. Since not all goods consumed in one particular country are produced in that country, the water footprint consists of two parts: use of domestic water resources and use of water outside the borders of the country.

The water footprint has been developed in analogy to the ecological footprint concept as was introduced in the 1990s (Rees, 1992; Wackernagel and Rees, 1996; Wackernagel *et al.*, 1997). The 'ecological footprint' of a population represents the area of productive land and aquatic ecosystems required to produce the resources used, and to assimilate the wastes produced, by a certain population at a specified material standard of living, wherever on earth that land may be located. Whereas the 'ecological footprint' thus quantifies the *area* needed to sustain people's living, the 'water footprint' indicates the *water* required to sustain a population.

The water footprint concept is closely linked to the virtual water concept. Virtual water is defined as the volume of water required to produce a commodity or service. The concept was introduced by Allan in the early 1990s (Allan, 1993, 1994) when studying the option of importing virtual water (as opposed to real water) as a partial solution to problems of water scarcity in the Middle East. Allan elaborated on the idea of using virtual water import (coming along with food imports) as a tool to release the pressure on the scarcely available domestic water resources. Virtual water import thus becomes an alternative water source, next to endogenous water sources. Imported virtual water has therefore also been called 'exogenous water' (Haddadin, 2003).

When assessing the water footprint of a nation, it is essential to quantify the flows of virtual water leaving and entering the country. If one takes the use of domestic water resources as a starting point for the assessment of a nation's water footprint, one should subtract the virtual water flows that leave the country and add the virtual water flows that enter the country.

The objective of this study is to assess and analyse the water footprints of nations. The study builds on two earlier studies. Hoekstra and Hung (2002, 2005) have quantified the virtual water flows related to the international trade of crop products. Chapagain and Hoekstra (2003) have done a similar study for livestock and livestock products. The concerned time period in these two studies is 1995–1999. The present study takes the period of 1997–2001 and refines the earlier studies by making a number of improvements and extensions.

Method

A nation's water footprint has two components, the internal and the external water footprint. The internal water footprint (*IWFP*) is defined as the use of domestic water resources to produce goods and services consumed by inhabitants of the country. It is the sum of the total water volume used from the domestic water resources in the national economy *minus* the volume of virtual water export to other countries insofar related to export of domestically produced products:

$$IWFP = AWU + IWW + DWW - VWE_{\text{dom}} \tag{1}$$

Here, *AWU* is the agricultural water use, taken equal to the evaporative water demand of the crops; *IWW* and *DWW* are the water withdrawals in the industrial and domestic sectors respectively; and VWE_{dom} is the virtual water export to other countries insofar related to export of domestically produced products. The agricultural water use includes both effective rainfall (the portion of the total precipitation which is retained by the soil and used for crop production) and the part of irrigation water used effectively for crop production. Here we do not include irrigation losses in the term of agricultural water use assuming that they largely return to the resource base and thus can be reused.

The external water footprint of a country (*EWFP*) is defined as the annual volume of water resources used in other countries to produce goods and services consumed by the inhabitants of the country concerned. It is equal to the so-called virtual water import into the country *minus* the volume of virtual water exported to other countries as a result of re-export of imported products.

$$EWFP = VWI - VWE_{\text{re-export}} \tag{2}$$

Both the internal and the external water footprint include the use of *blue water* (ground and surface water) and the use of *green water* (moisture stored in soil strata).

The use of domestic water resources comprises water use in the agricultural, industrial and domestic sectors. For the latter two sectors we have used data from AQUASTAT (FAO, 2003). Though significant fractions of domestic and industrial water withdrawals do not evaporate but return to either the groundwater or surface water system, these return flows are generally polluted, so that they have been included in the water footprint calculations. The total volume of water use in the agricultural sector has been calculated in this study based on the total volume of crop produced and its corresponding virtual water content. For the calculation of the virtual water content of crop and livestock products we have used the methodology as described in Chapagain and Hoekstra (2004). In summary, the virtual water content (m^3/ton) of primary crops has been calculated based on crop water requirements and yields. Crop water requirement have been calculated per crop and per country using the methodology developed by FAO (Allen *et al.*, 1998). The virtual water content of crop products is calculated based on product fractions (ton of crop product obtained per ton of primary crop) and value fractions (the market value of one crop product divided by the aggregated market value of all crop products derived from one primary crop). The virtual water content (m^3/ton) of live animals has been calculated based on the virtual water content of their feed and the volumes of drinking and service water consumed during their lifetime. We have calculated the virtual water content for eight major animal categories: beef cattle, dairy cows, swine, sheep, goats, fowls/poultry (meat purpose), laying hens and horses. The calculation of the virtual water content of livestock products is again based on product fractions and value fractions.

Virtual water flows between nations have been calculated by multiplying commodity trade flows by their associated virtual water content:

$$VWF[n_e, n_i, c] = CT[n_e, n_i, c] \times VWC[n_e, c] \tag{3}$$

in which *VWF* denotes the virtual water flow ($m^3 yr^{-1}$) from exporting country n_e to importing country n_i as a result of trade in commodity c; *CT* the commodity trade (ton yr^{-1}) from the exporting to the importing country; and *VWC* the virtual water content (m^3 ton^{-1}) of the commodity, which is defined as the volume of water required to produce the commodity in the exporting country. We have taken into account the trade between 243 countries for which international trade data are available in the Personal Computer Trade Analysis System of the International Trade Centre, produced in collaboration with UNCTAD/WTO. It covers trade data from 146 reporting countries disaggregated by product and partner countries (ITC, 2004). We have carried out calculations for 285 crop products and 123 livestock products. The virtual water content of an industrial product can be calculated in a similar way as described earlier for agricultural products. There are however numerous categories of industrial products with a diverse range of production methods and detailed standardised national statistics related to the production and consumption of industrial products are hard to find. As the global volume of water used in the industrial sector is only 716 Gm^3/yr ($\approx$10% of total global water use), we have – per country – simply calculated an average virtual water content per dollar added value in the industrial sector (m^3/US$) as the ratio of the industrial water withdrawal (m^3/yr) in a country to the total added value of the industrial sector (US$ /yr), which is a component of the Gross Domestic Product.

Water needs by product

The total volume of water used globally for crop production is 6390 Gm^3/yr at field level. Rice has the largest share in the total volume water used for global crop production. It consumes about 1359 Gm^3/yr, which is about 21% of the total volume of water used for crop production at field level. The second largest water consumer is wheat (12%). The contribution of some major crops to the global water footprint insofar related to food consumption is presented in Figure 1. Although the total volume of the world rice production is about equal to the wheat production, rice consumes much more water per ton of production. The difference is due

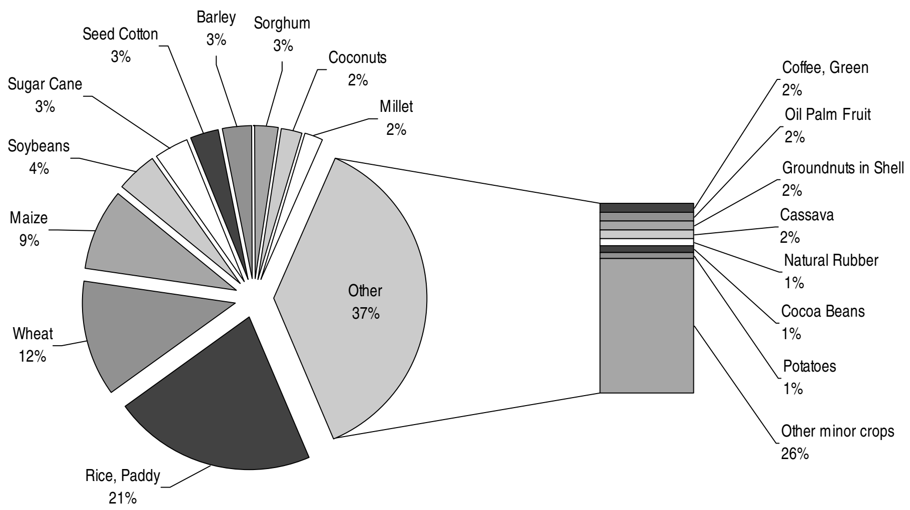

Fig. 1 Contribution of different crops to the global water footprint

to the higher evaporative demand for rice production. As a result, the global average virtual water content of rice (paddy) is 2291 m^3/ton and for wheat 1334 m^3/ton.

The virtual water content of rice (broken) that a consumer buys in the shop is about 3420 m^3/ton. This is larger than the virtual water content of paddy rice as harvested from the field because of the weight loss if paddy rice is processed into broken rice. The virtual water content of some selected crop and livestock products for a number of selected countries are presented in Table 1.

In general, livestock products have a higher virtual water content than crop products. This is because a live animal consumes a lot of feed crops, drinking water and service water in its lifetime before it produces some output. We consider here an example of beef produced in an industrial farming system. It takes in average 3 years before it is slaughtered to produce about 200 kg of boneless beef. It consumes nearly 1300 kg of grains (wheat, oats, barley, corn, dry peas, soybean meal and other small grains), 7200 kg of roughages (pasture, dry hay, silage and other roughages), 24 cubic meter of water for drinking and 7 cubic meter of water for servicing. This means that to produce one kilogram of boneless beef, we use about 6.5 kg of grain, 36 kg of roughages, and 155 l of water (only for drinking and servicing). Producing the volume of feed requires about 15340 l of water in average. With every step of food processing we loose part of the material as a result of selection and inefficiencies. The higher we go up in the product chain, the higher will be the virtual water content of the product. For example, the global average virtual water content of maize, wheat and rice (husked) is 900, 1300 and 3000 m^3/ton respectively, whereas the virtual water content of chicken meat, pork and beef is 3900, 4900 and 15500 m^3/ton respectively. However, the virtual water content of products strongly varies from place to place, depending upon the climate, technology adopted for farming and corresponding yields.

The units used so far to express the virtual water content of various products are in terms of cubic meters of water per ton of the product. A consumer might be more interested to know how much water it consumes per unit of consumption. One cup of coffee requires for instance 140 l of water in average, one hamburger 2400 l and one cotton T-shirt 2000 l (Table 2).

The global average virtual water content of industrial products is 80 l per US$. In the USA, industrial products take nearly 100 l per US$. In Germany and the Netherlands, average virtual water content of industrial products is about 50 l per US$. Industrial products from Japan, Australia and Canada take only 10–15 l per US$. In world's largest developing nations, China and India, the average virtual water content of industrial products is 20–25 l per US$.

Water footprints of nations

The global water footprint is 7450 Gm^3/yr, which is 1240 m^3/cap/yr in average. In absolute terms, India is the country with the largest footprint in the world, with a total footprint of 987 Gm^3/yr. However, while India contributes 17% to the global population, the people in India contribute only 13% to the global water footprint. On a relative basis, it is the people of the USA that have the largest water footprint, with 2480 m^3/yr per capita, followed by the people in south European countries such as Greece, Italy and Spain (2300–2400 m^3/yr per capita). High water footprints can also be found in Malaysia and Thailand. At the other side of the scale, the Chinese people have a relatively low water footprint with an average of 700 m^3/yr per capita. The average per capita water footprints of nations are shown in Figure 2. The data are shown in Table 3 for a few selected countries.

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Table 1 Average virtual water content of some selected products for a number of selected countries (m^3/ton)

	USA	China	India	Russia	Indonesia	Australia	Brazil	Japan	Mexico	Italy	Netherlands	World average*
Rice (paddy)	1275	1321	2850	2401	2150	1022	3082	1221	2182	1679		2291
Rice (husked)	1656	1716	3702	3118	2793	1327	4003	1586	2834	2180		2975
Rice (broken)	1903	1972	4254	3584	3209	1525	4600	1822	3257	2506		3419
Wheat	849	690	1654	2375		1588	1616	734	1066	2421	619	1334
Maize	489	801	1937	1397	1285	744	1180	1493	1744	530	408	909
Soybeans	1869	2617	4124	3933	2030	2106	1076	2326	3177	1506		1789
Sugar cane	103	117	159		164	141	155	120	171			175
Cotton seed	2535	1419	8264		4453	1887	2777		2127			3644
Cotton lint	5733	3210	18694		10072	4268	6281		4812			8242
Barley	702	848	1966	2359		1425	1373	697	2120	1822	718	1388
Sorghum	782	863	4053	2382		1081	1609		1212	582		2853
Coconuts		749	2255		2071		1590		1954			2545
Millet	2143	1863	3269	2892		1951		3100	4534			4596
Coffee (green)	4864	6290	12180		17665		13972		28119			17373
Coffee (roasted)	5790	7488	14500		21030		16633		33475			20682
Tea (made)		11110	7002	3002	9474		6592	4940				9205
Beef	13193	12560	16482	21028	14818	17112	16961	11019	37762	21167	11681	15497
Pork	3946	2211	4397	6947	3938	5909	4818	4962	6559	6377	3790	4856
Goat meat	3082	3994	5187	5290	4543	3839	4175	2560	10252	4180	2791	4043
Sheep meat	5977	5202	6692	7621	5956	6947	6267	3571	16878	7572	5298	6143
Chicken meat	2389	3652	7736	5763	5549	2914	3913	2977	5013	2198	2222	3918
Eggs	1510	3550	7531	4919	5400	1844	3337	1884	4277	1389	1404	3340
Milk	695	1000	1369	1345	1143	915	1001	812	2382	861	641	990
Milk powder	3234	4648	6368	6253	5317	4255	4654	3774	11077	4005	2982	4602
Cheese	3457	4963	6793	6671	5675	4544	4969	4032	11805	4278	3190	4914
Leather (bovine)	14190	13513	17710	22575	15929	18384	18222	11864	40482	22724	12572	16656

* For the primary crops, world averages have been calculated as the ratio of the global water use for the production of a crop to the global production volume. For processed products, the global averages have been calculated as the ratio of the global virtual water trade volume to the global product trade volume.

Table 2 Global average virtual water content of some selected products, per unit of product

Product	Virtual water content (litres)
1 glass of beer (250 ml)	75
1 glass of milk (200 ml)	200
1 cup of coffee (125 ml)	140
1 cup of tea (250 ml)	35
1 slice of bread (30 g)	40
1 slice of bread (30 g) with cheese(10 g)	90
1 potato (100 g)	25
1 apple (100 g)	70
1 cotton T-shirt (250 g)	2000
1 sheet of A4-paper (80 g/m^2)	10
1 glass of wine (125 ml)	120
1 glass of apple juice (200 ml)	190
1 glass of orange juice (200 ml)	170
1 bag of potato crisps (200 g)	185
1 egg (40 g)	135
1 hamburger (150 g)	2400
1 tomato (70 g)	13
1 orange (100 g)	50
1 pair of shoes (bovine leather)	8000
1 microchip (2 g)	32

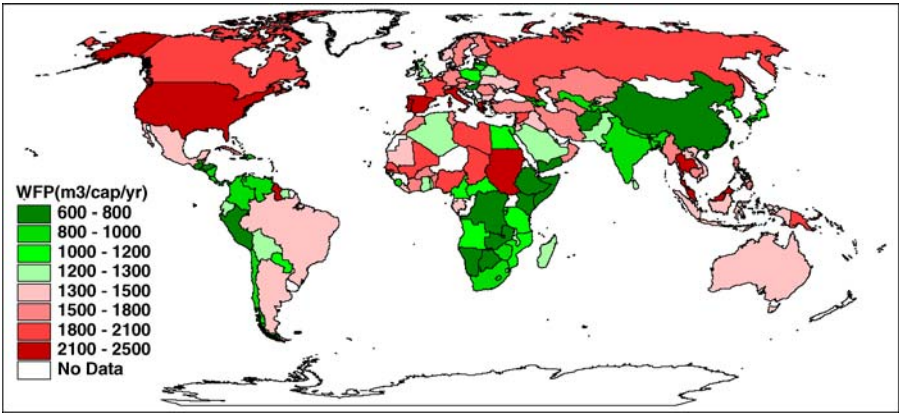

Fig. 2 Average national water footprint per capita (m^3/capita/yr). Green means that the nation's water footprint is equal to or smaller than global average. Countries with red have a water footprint beyond the global average

The size of the global water footprint is largely determined by the consumption of food and other agricultural products (Figure 3). The estimated contribution of agriculture to the total water use (6390 Gm^3/yr) is even bigger than suggested by earlier statistics due to the inclusion of green water use (use of soil water). If we include irrigation losses, which globally add up to about 1590 Gm^3/yr (Chapagain and Hoekstra, 2004), the total volume of water used in agriculture becomes 7980 Gm^3/yr. About one third of this amount is blue water withdrawn for irrigation; the remaining two thirds is green water (soil water).

The four major direct factors determining the water footprint of a country are: volume of consumption (related to the gross national income); consumption pattern (e.g. high versus

Table 3 Composition of the water footprint for some selected countries. Period: 1997–2001

Country	Population	Use of domestic water resources: Domestic water withdrawal (Gm^3/yr)	Use of domestic water resources: Crop evapotranspiration*: For national consumption (Gm^3/yr)	Crop evapotranspiration*: For export (Gm^3/yr)	Industrial water withdrawal: For national consumption (Gm^3/yr)	Industrial water withdrawal: For export (Gm^3/yr)	Use of foreign water resources: For national consumption: Agricultural goods (Gm^3/yr)	For national consumption: Industrial goods (Gm^3/yr)	For re-export of imported products (Gm^3/yr)	Water footprint: Total (Gm^3/yr)	Water footprint: Per capita (m^3/cap/yr)	Water footprint by consumption category: Domestic water: Internal water footprint (m^3/cap/yr)	Agricultural goods: Internal water footprint (m^3/cap/yr)	Agricultural goods: External water footprint (m^3/cap/yr)	Industrial goods: Internal water footprint (m^3/cap/yr)	Industrial goods: External water footprint (m^3/cap/yr)
Australia	19071705	6.51	14.03	68.67	1.229	0.12	0.78	4.02	4.21	26.56	1393	341	736	41	64	211
Bangladesh	129942975	2.12	109.98	1.38	0.344	0.08	3.71	0.34	0.13	116.49	896	16	846	29	3	3
Brazil	169109675	11.76	195.29	61.01	8.666	1.63	14.76	3.11	5.20	233.59	1381	70	1155	87	51	18
Canada	30649675	8.55	30.22	52.34	11.211	20.36	7.74	5.07	22.62	62.80	2049	279	986	252	366	166
China	1257521250	33.32	711.10	21.55	81.531	45.73	49.99	7.45	5.69	883.39	702	26	565	40	65	6
Egypt	63375735	4.16	45.78	1.55	6.423	0.66	12.49	0.64	0.49	69.50	1097	66	722	197	101	10
France	58775400	6.16	47.84	34.63	15.094	12.80	30.40	10.69	31.07	110.19	1875	105	814	517	257	182
Germany	82169250	5.45	35.64	18.84	18.771	13.15	49.59	17.50	38.48	126.95	1545	66	434	604	228	213
India	1007369125	38.62	913.70	35.29	19.065	6.04	13.75	2.24	1.24	987.38	980	38	907	14	19	2
Indonesia	204920450	5.67	236.22	22.62	0.404	0.06	26.09	1.58	2.74	269.96	1317	28	1153	127	2	8
Italy	57718000	7.97	47.82	12.35	10.133	5.60	59.97	8.69	20.29	134.59	2332	138	829	1039	176	151
Japan	126741225	17.20	20.97	0.40	13.702	2.10	77.84	16.38	4.01	146.09	1153	136	165	614	108	129
Jordan	4813708	0.21	1.45	0.07	0.035	0.00	4.37	0.21	0.22	6.27	1303	44	301	908	7	43
Mexico	97291745	13.55	81.48	12.26	2.998	1.13	35.09	7.05	7.94	140.16	1441	139	837	361	31	72
Netherlands	15865250	0.44	0.50	2.51	2.562	2.20	9.30	6.61	52.84	19.40	1223	28	31	586	161	417
Pakistan	136475525	2.88	152.75	7.57	1.706	1.28	8.55	0.33	0.67	166.22	1218	21	1119	63	12	2
Russia	145878750	14.34	201.26	8.96	13.251	34.83	41.33	0.80	3.94	270.98	1858	98	1380	283	91	5
South Africa	42387403	2.43	27.32	6.05	1.123	0.40	7.18	1.42	2.10	39.47	931	57	644	169	26	33
Thailand	60487800	1.83	120.17	38.49	1.239	0.55	8.73	2.49	3.90	134.46	2223	30	1987	144	20	41
United Kingdom	58669403	2.21	12.79	3.38	6.673	1.46	34.73	16.67	12.83	73.07	1245	38	218	592	114	284
USA	280343325	60.80	334.24	138.96	170.777	44.72	74.91	55.29	45.62	696.01	2483	217	1192	267	609	197
Global total/avg.	5994251631	344	5434	957	476	240	957	240	427	7452	1243	57	907	160	79	40

* Includes both blue and green water use in agriculture

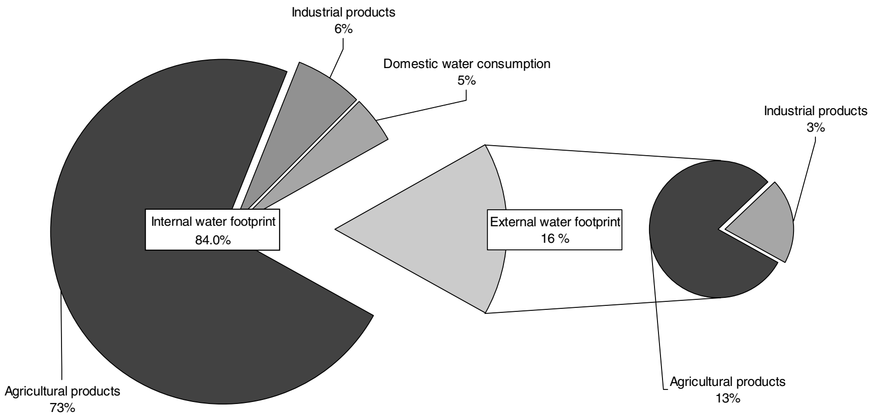

Fig. 3 Contribution of different consumption categories to the global water footprint, with a distinction between the internal and external footprint

low meat consumption); climate (growth conditions); and agricultural practice (water use efficiency). In rich countries, people generally consume more goods and services, which immediately translates into increased water footprints. But it is not consumption volume alone that determines the water demand of people. The composition of the consumption package is relevant too, because some goods in particular require a lot of water (bovine meat, rice). In many poor countries it is a combination of unfavourable climatic conditions (high evaporative demand) and bad agricultural practice (resulting in low water productivity) that contributes to a high water footprint. Underlying factors that contribute to bad agricultural practice and thus high water footprints are the lack of proper water pricing, the presence of subsidies, the use of water inefficient technology and lack of awareness of simple water saving measures among farmers.

The influence of the various determinants varies from country to country. The water footprint of the USA is high (2480 m^3/cap/yr) partly because of large meat consumption per capita and high consumption of industrial products. The water footprint of Iran is relatively high (1624 m^3/cap/yr) partly because of low yields in crop production and partly because of high evapotranspiration. In the USA the industrial component of the water footprint is 806 m^3/cap/yr whereas in Iran it is only 24 m^3/cap/yr.

The aggregated external water footprints of nations in the world constitute 16% of the total global water footprint (Figure 3). However, the share of the external water footprint strongly varies from country to country. Some African countries, such as Sudan, Mali, Nigeria, Ethiopia, Malawi and Chad have hardly any external water footprint, simply because they have little import. Some European countries on the other hand, e.g. Italy, Germany, the UK and the Netherlands have external water footprints contributing 50–80% to the total water footprint. The agricultural products that contribute most to the external water footprints of nations are: bovine meat, soybean, wheat, cocoa, rice, cotton and maize.

Eight countries – India, China, the USA, the Russian Federation, Indonesia, Nigeria, Brazil and Pakistan – together contribute fifty percent to the total global water footprint. India (13%), China (12%) and the USA (9%) are the largest consumers of the global water resources (Figure 4).

Both the size of the national water footprint and its composition differs between countries (Figure 5). On the one end we see China with a relatively low water footprint per capita, and on

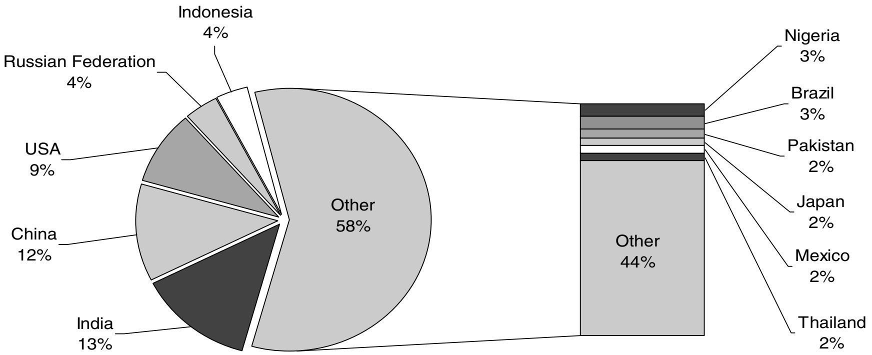

Fig. 4 Contribution of major consumers to the global water footprint

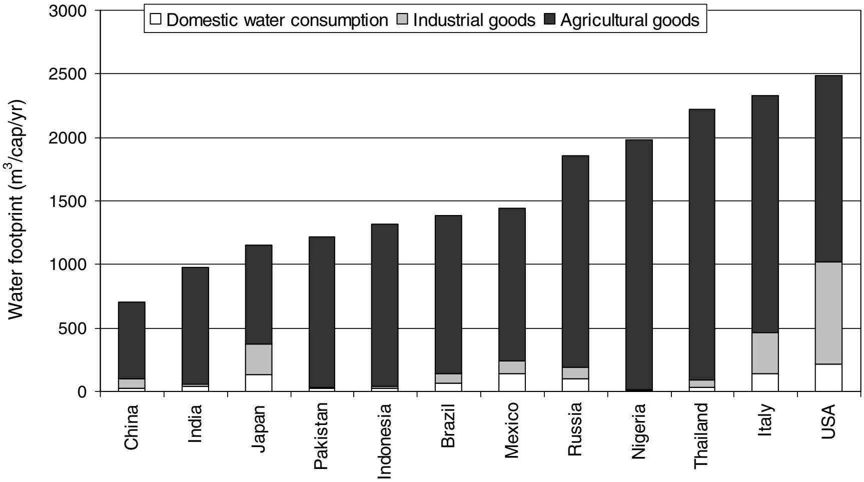

Fig. 5 The national water footprint per capita and the contribution of different consumption categories for some selected countries

the other end the USA. In the rich countries consumption of industrial goods has a relatively large contribution to the total water footprint if compared with developing countries. The water footprints of the USA, China, India and Japan are presented in more detail in Figure 6. The contribution of the external water footprint to the total water footprint is very large in Japan if compared to the other three countries. The consumption of industrial goods very significantly contributes to the total water footprint of the USA (32%), but not in India (2%).

Conclusion

The global water footprint is 7450 Gm^3/yr, which is in average 1240 m^3/cap/yr. The differences between countries are large: the USA has an average water footprint of 2480 m^3/cap/yr whereas China has an average water footprint of 700 m^3/cap/yr. There are four most important direct factors explaining high water footprints. A first factor is the total volume of

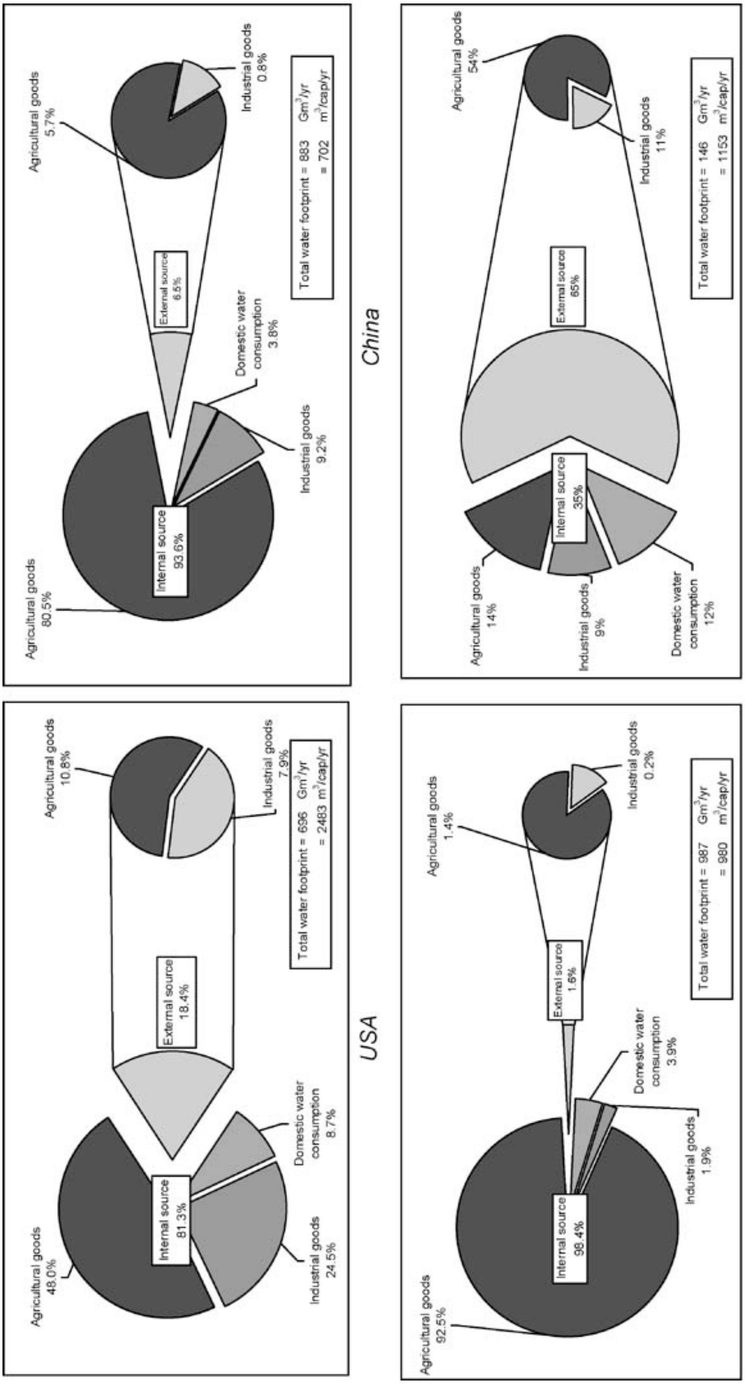

Fig. 6 Details of the water footprints of the USA, China India and Japan. Period: 1997–2001

consumption, which is generally related to gross national income of a country. This partially explains the high water footprints of for instance the USA, Italy and Switzerland. A second factor behind a high water footprint can be that people have a water-intensive consumption pattern. Particularly high consumption of meat significantly contributes to a high water footprint. This factor partially explains the high water footprints of countries such as the USA, Canada, France, Spain, Portugal, Italy and Greece. The average meat consumption in the United States is for instance 120 kg/yr, more than three times the world-average meat consumption. Next to meat consumption, high consumption of industrial goods significantly contributes to the total water footprints of rich countries. The third factor is climate. In regions with a high evaporative demand, the water requirement per unit of crop production is relatively large. This factor partially explains the high water footprints in countries such as Senegal, Mali, Sudan, Chad, Nigeria and Syria. A fourth factor that can explain high water footprints is water-inefficient agricultural practice, which means that water productivity in terms of output per drop of water is relatively low. This factor partly explains the high water footprints of countries such as Thailand, Cambodia, Turkmenistan, Sudan, Mali and Nigeria. In Thailand for instance, rice yields averaged 2.5 ton/ha in the period 1997–2001, while the global average in the same period was 3.9 ton/ha.

Reducing water footprints can be done in various ways. A first way is to break the seemingly obvious link between economic growth and increased water use, for instance by adopting production techniques that require less water per unit of product. Water productivity in agriculture can be improved for instance by applying advanced techniques of rainwater harvesting and supplementary irrigation. A second way of reducing water footprints is to shift to consumptions patterns that require less water, for instance by reducing meat consumption. However, it has been debated whether this is a feasible road to go, since the world-wide trend has been that meat consumption increases rather than decreases. Probably a broader and subtler approach will be needed, where consumption patterns are influenced by pricing, awareness raising, labelling of products or introduction of other incentives that make people change their consumption behaviour. Water costs are generally not well reflected in the price of products due to the subsidies in the water sector. Besides, the general public is – although often aware of energy requirements – hardly aware of the water requirements in producing their goods and services.

A third method that can be used – not yet broadly recognized as such – is to shift production from areas with low water-productivity to areas with high water productivity, thus increasing global water use efficiency (Chapagain *et al.*, 2005a). For instance, Jordan has successfully externalised its water footprint by importing wheat and rice products from the USA, which has higher water productivity than Jordan.

The water footprint of a nation is an indicator of water use in relation to the consumption volume and pattern of the people. As an aggregated indicator it shows the total water requirement of a nation, a rough measure of the impact of human consumption on the natural water environment. More information about the precise components and characteristics of the total water footprint will be needed, however, before one can make a more balanced assessment of the effects on the natural water systems. For instance, one has to look at what is blue versus green water use, because use of blue water often affects the environment more than green water use. Also it is relevant to consider the internal versus the external water footprint. Externalising the water footprint for instance means externalising the environmental impacts. Also one has to realise that some parts of the total water footprint concern use of water for which no alternative use is possible, while other parts relate to water that could have been used for other purposes with higher added value. There is a difference for instance between beef produced in extensively grazed grasslands of Botswana (use of green water without alternative use) and beef produced in an industrial livestock farm in the Netherlands (partially fed with imported irrigated feed crops).

The current study has focused on the quantification of consumptive water use, i.e. the volumes of water from groundwater, surface water and soil water that evaporate. The effect of water pollution was accounted for to a limited extent by including the (polluted) return flows in the domestic and industrial sector. The calculated water footprints thus consists of two components: consumptive water use and wastewater production. The effect of pollution has been underestimated however in the current calculations of the national water footprints, because one cubic metre of wastewater should not count for one, because it generally pollutes much more cubic metres of water after disposal (various authors have suggested a factor of ten to fifty). The impact of water pollution can be better assessed by quantifying the dilution water volumes required to dilute waste flows to such extent that the quality of the water remains below agreed water quality standards. We have shown this in a case study for the water footprints of nations related to cotton consumption (Chapagain *et al.*, 2005b).

International water dependencies are substantial and are likely to increase with continued global trade liberalisation. Today, 16% of global water use is not for producing products for domestic consumption but for making products for export. Considering this substantial percentage and the upward trend, we suggest that future national and regional water policy studies should include an analysis of international or interregional virtual water flows.

References

Allan JA (1993) Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible. In: Priorities for water resources allocation and management, ODA, London, pp 13–26

Allan JA (1994) Overall perspectives on countries and regions. In: Rogers P, Lydon P (eds) Water in the Arab World: perspectives and prognoses. Harvard University Press, Cambridge, Massachusetts, pp 65–100

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration - Guidelines for computing crop water requirements – FAO Irrigation and Drainage Paper 56, FAO, Rome, Italy, http://www.fao.org/docrep/X0490E/x0490e00.htm

Chapagain AK, Hoekstra AY (2003) Virtual water flows between nations in relation to trade in livestock and livestock products. Value of Water Research Report Series No. 13, UNESCO-IHE, Delft, The Netherlands, http://www.waterfootprint.org/Reports/Report13.pdf

Chapagain AK, Hoekstra AY, Savenije HHG (2005a) Saving water through global trade. Value of Water Research Report Series No. 17, UNESCO-IHE, Delft, the Netherlands, http://www.waterfootprint.org/Reports/Report17.pdf

Chapagain AK, Hoekstra AY, Savenije HHG, Gautam R (2005b) The water footprint of cotton consumption. Value of Water Research Report Series No. 18, UNESCO-IHE, The Netherlands, http://www.waterfootprint.org/Reports/Report18.pdf

Chapagain AK, Hoekstra AY (2004) Water footprints of nations. Value of Water Research Report Series No. 16, UNESCO-IHE, Delft, The Netherlands, http://www.waterfootprint.org/Reports/Report16.pdf

FAO (2003) AQUASTAT 2003. Food and Agriculture Organization of the United Nations, Rome, Italy, ftp://ftp.fao.org/agl/aglw/aquastat/aquastat2003.xls

Gleick PH (ed) (1993) Water in crisis: A guide to the world's fresh water resources. Oxford University Press, Oxford, UK

Haddadin MJ (2003) Exogenous water: A conduit to globalization of water resources. In: Hoekstra AY (ed) Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series No. 12, UNESCO-IHE, Delft, The Netherlands, http://www.waterfootprint.org/Reports/Report12.pdf

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 No. 11, UNESCO-IHE Institute for Water Education, Delft, The Netherlands, http://www.waterfootprint.org/Reports/Report11.pdf

Hoekstra AY, Hung PQ (2005) Globalisation of water resources: International virtual water flows in relation to crop trade. Global Environmental Change 15(1):45–56

ITC (2004) PC-TAS version 1997–2001 in HS or SITC, CD-ROM. International Trade Centre, Geneva

Rees WE (1992) Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environ Urban 4(2):121–130

Shiklomanov IA (2000) Appraisal and assessment of world water resources. Water International 25(1):11–32

Wackernagel M, Onisto L, Linares AC, Falfan ISL, Garcia JM, Guerrero IS, Guerrero MGS (1997) Ecological footprints of nations: How much nature do they use? How much nature do they have?. Centre for Sustainability Studies, Universidad Anahuac de Xalapa, Mexico

Wackernagel M, Rees W (1996) Our ecological footprint: Reducing human impact on the Earth. New Society Publishers, Gabriola Island, BC, Canada

Carbon Calculators for Lab 2

1. The Nature Conservancy's Carbon Calculator
    a. http://www.nature.org/initiatives/climatechange/calculator/
2. Terrapass
    a. : http://terrapass.com/carbon-footprint-calculator/
3. UC Berkeley Institute of the Environment CoolClimate Carbon Footprint Calculator
    a. http://coolclimate.berkeley.edu/
4. www.carbonfootprint.com/calculator.aspx
5. EPA Greenhouse Gas Household Emissions Calculator
    a. http://www.epa.gov/climatechange/emissons/ind_calculator.html
6. Yahoo! Green Carbon Footprint Calculator
    a. http://green.yahoo.com/calculator