ECOLOGICAL ECONOMICS 60 (2006) 186–203

available at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/ecolecon

ANALYSIS

The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries

A.K. Chapagain [a], A.Y. Hoekstra [b,*], H.H.G. Savenije [a], R. Gautam [c]

[a]UNESCO-IHE Institute for Water Education, Delft, the Netherlands
[b]University of Twente, Enschede, the Netherlands
[c]Association for Protection of Environment and Culture, Morang, Nepal

ARTICLE INFO

Article history:
Received 20 July 2005
Received in revised form
29 November 2005
Accepted 30 November 2005
Available online 9 March 2006

Keywords:
Cotton consumption
Water footprint
Green water
Blue water
Virtual water
Water pollution

ABSTRACT

The consumption of a cotton product is connected to a chain of impacts on the water resources in the countries where cotton is grown and processed. The aim of this paper is to assess the 'water footprint' of worldwide cotton consumption, identifying both the location and the character of the impacts. The study distinguishes between three types of impact: evaporation of infiltrated rainwater for cotton growth (green water use), withdrawal of ground- or surface water for irrigation or processing (blue water use) and water pollution during growth or processing. The latter impact is quantified in terms of the dilution volume necessary to assimilate the pollution. For the period 1997–2001 the study shows that the worldwide consumption of cotton products requires 256 Gm^3 of water per year, out of which about 42% is blue water, 39% green water and 19% dilution water. Impacts are typically cross-border. About 84% of the water footprint of cotton consumption in the EU25 region is located outside Europe, with major impacts particularly in India and Uzbekistan. Given the general lack of proper water pricing mechanisms or other ways of transmitting production-information, cotton consumers have little incentive to take responsibility for the impacts on remote water systems.

1. Introduction

Globally, freshwater resources are becoming scarcer due to an increase in population and subsequent increase in water appropriation and deterioration of water quality (Postel et al., 1996; Shiklomanov, 2000; Vörösmarty et al., 2000; Vörösmarty and Sahagian, 2000). The impact of consumption of people on the global water resources can be mapped with the concept of the 'water footprint', a concept introduced by Hoekstra and Hung (2002) and subsequently elaborated by Chapagain and Hoekstra (2004). The water footprint of a nation has been defined as the total volume of freshwater that is used to produce the goods and services consumed by the inhabitants of the nation. It deviates from earlier indicators of water use in the fact that the water footprint shows water demand related to *consumption* within a nation, while the earlier indicators (e.g. total water withdrawal for the various sectors of economy) show water demand in relation to *production* within a nation. The current paper focuses on the assessment and analysis of the water footprints of nations insofar related to the consumption of cotton products. The period 1997–2001 has been taken as the period of analysis.

* *Corresponding author.* Tel.: +31 53 489 3880; fax: +31 53 489 5377.
E-mail address: a.y.hoekstra@utwente.nl (A.Y. Hoekstra).

0921-8009/$ - see front matter
doi:10.1016/j.ecolecon.2005.11.027

The water footprint concept is an analogue of the ecological footprint concept that was introduced in the 1990s (Rees, 1992; Wackernagel and Rees, 1996; Wackernagel et al., 1997, 1999). Whereas the ecological footprint denotes the *area* (ha) needed to sustain a population, the water footprint represents the *water volume* (cubic metres per year) required.

Earlier water-footprint studies were limited to the quantification of resource use, i.e. the use of groundwater, surface water and soil water (Hoekstra and Hung, 2002; Chapagain and Hoekstra, 2003a,b, 2004). The current study extends the water footprint concept through quantifying the impacts of pollution as well. This has been done 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. The rationale for including this water component in the definition of the water footprint is similar to the rationale for including the land area needed for uptake of anthropogenic carbon dioxide emissions in the definition of the ecological footprint. Land and water do not function as resource bases only, but as systems for waste assimilation as well. We realise that the method to translate the impacts of pollution into water requirements as applied in this study can potentially invoke a similar debate as is being held about the methods applied to translate the impacts of carbon dioxide emissions into land requirements (see e.g. Van den Bergh and Verbruggen, 1999; Van Kooten and Bulte, 2000). We would welcome such a debate, because of the societal need for proper natural resources accounting systems on the one hand and the difficulties in achieving the required scientific rigour in the accounting procedures on the other hand. The approach introduced in the current study should be seen as a first step; we will reflect in terms of possible improvements in the conclusions.

Some of the earlier studies on the impacts of cotton production were limited to the impacts in the industrial stage only (e.g. Ren, 2000), leaving out the impacts in the agricultural stage. Other cotton impact studies use the method of life cycle analysis and thus include all stages of production, but these studies are focussed on methodology rather than the quantification of the impacts (e.g. Proto et al., 2000; Seuring, 2004). Earlier studies that go in the direction of what we aim at in this paper are the background studies for the cotton initiative of the World Wide Fund for Nature (Soth et al., 1999; De Man, 2001). In our study, however, we aim to synthesize the various impacts of cotton on water in one comprehensive indicator, the water footprint, and we introduce the spatial dimension by showing how water footprints of some nations particularly press in other parts of the world.

Cotton is the most important natural fibre used in the textile industries worldwide. Today, cotton takes up about 40% of textile production, while synthetic fibres take up about 55% (Proto et al., 2000; Soth et al., 1999). During the period 1997–2001, international trade in cotton products constitutes 2% of the global merchandise trade value.

The impacts of cotton production on the environment are easily visible and have different faces. On the one hand there are the effects of water depletion, on the other hand the effects on water quality. In many of the major textile processing areas, downstream riparians can see from the river what was the latest colour applied in the upstream textile industry. The Aral Sea is the most famous example of the effects of water abstractions for irrigation. In the period 1960–2000, the Aral Sea in Central Asia lost approximately 60% of its area and 80% of its volume (Glantz, 1998; Hall et al., 2001; Pereira et al., 2002; UNEP, 2002; Loh and Wackernagel, 2004) as a result of the annual abstractions of water from the Amu Darya and the Syr Darya–the rivers which feed the Aral Sea–to grow cotton in the desert.

About 53% of the global cotton field is irrigated, producing 73% of the global cotton production (Soth et al., 1999). Irrigated cotton is mainly grown in the Mediterranean and other warm climatic regions, where freshwater is already in short supply. Irrigated cotton is mainly located in dry regions: Egypt, Uzbekistan, and Pakistan. The province Xinjiang of China is entirely irrigated, whereas in Pakistan and the North of India a major portion of the crop water requirements of cotton are met by supplementary irrigation. As a result, in Pakistan already 31% of all irrigation water is drawn from ground water and in China the extensive freshwater use has caused falling water tables (Soth et al., 1999). Nearly 70% of the world's cotton crop production is from China, USA, India, Pakistan and Uzbekistan (USDA, 2004). Most of the cotton productions rely on a furrow irrigation system. Sprinkler and drip systems are also adopted as an irrigated method in water scarce regions. However, hardly about 0.7% of land in the world is irrigated by this method (Postel, 1992).

2. Green, blue and dilution water

From field to end product, cotton passes through a number of distinct production stages with different impacts on water resources. These stages of production are often carried out at different locations and consumption can take place at yet another place. For instance, Malaysia does not grow cotton, but imports raw cotton from China, India and Pakistan for processing in the textile industry and exports cotton clothes to the European market. For that reason the impacts of consumption of a final cotton product can only be found by tracing the origins of the product. The relation between the production stages and their impacts on the environment is shown in Fig. 1.

Although the chain from cotton growth to final product can take several distinct steps, there are two major stages: the agricultural stage (cotton production at field level) and the industrial stage (processing of seed cotton into final cotton products). In the first stage, there are three types of impact: evaporation of infiltrated rainwater for cotton growth, withdrawal of ground- or surface water for irrigation, and water pollution due to the leaching of fertilisers and pesticides. Based on Falkenmark (2003), we use the terms 'green water use' and 'blue water use' to distinguish between two different types of water source (either infiltrated rainwater or ground/surface water). 'Green water use' is quantitatively defined in the current paper as the volume of water taken up by plants from the soil insofar it concerns soil water originating from infiltrated rainwater. 'Blue water use' refers to the water taken up by plants from the soil

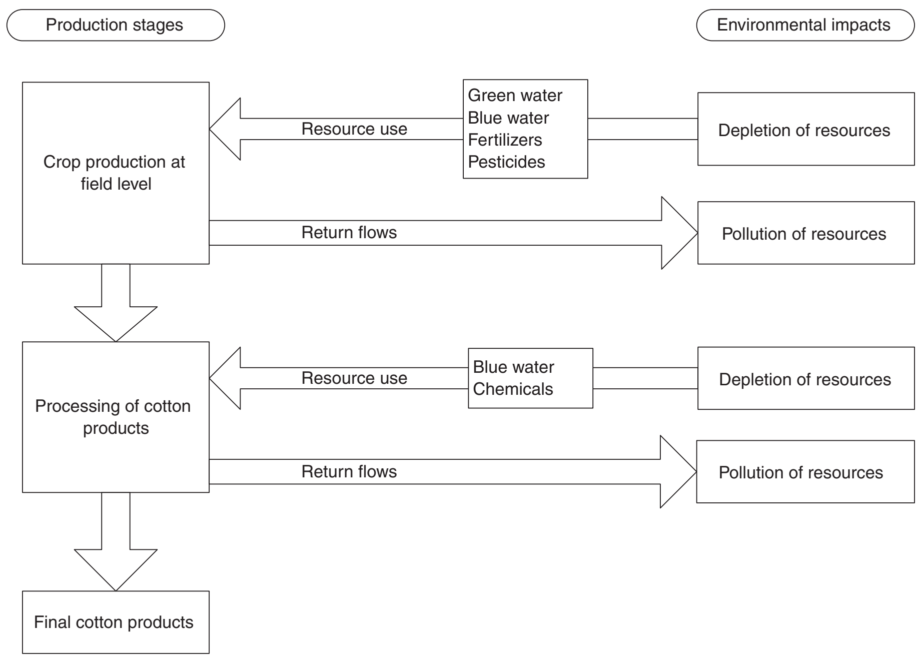

Fig. 1 – Impact of cotton production on the natural resources.

insofar it concerns infiltrated irrigation water. The latter definition provides a conservative estimate of blue water use, because the volume of withdrawal from ground- or surface water for irrigation is larger than the volume that is ultimately taken up by the plants. The difference consists of 'losses' due to infiltration or evaporation during transport and application. These 'losses' however are available again insofar they concern infiltration losses. The impact on water quality is quantified here and made comparable to the impacts of water use by translating the volumes of emitted chemicals into the dilution volume necessary to assimilate the pollution. In the industrial stage, there are two major impacts on water: abstraction of process water from surface or groundwater (blue water use), and pollution of water as a result of the waste flows from the cotton processing industries. The latter is again translated into a certain volume of dilution water requirement.

3. Virtual water

In order to assess the water footprint of cotton consumption in a country we need to know the use of domestic water resources for domestic cotton growth or processing and we need to know the water use associated with the import and export of raw cotton or cotton products. The total water footprint of a country includes two components: the part of the footprint that falls inside the country (internal water footprint) and the part of the footprint that presses on other countries in the world (external water footprint). The distinction refers to use of domestic water resources versus the use of foreign water resources (Chapagain and Hoekstra, 2004).

International trade of commodities brings along international flows of 'virtual water' (Hoekstra and Hung, 2005). 'Virtual water' is thereby defined as the volume of water used to produce a commodity (Allan, 1997, 1998). 'Virtual water' has also been called 'embedded water' and is a similar concept as 'embodied energy', which has been defined as the direct and indirect energy required to produce a good, service or entity (Herendeen, 2004). In accounting virtual water flows we keep track of which parts of these flows refer to green, blue and dilution water respectively.

4. The virtual water content of seed cotton

The virtual water content of seed cotton (m^3/ton) has been calculated as the ratio of the volume of water (m^3/ha) used during the entire period of crop growth to the corresponding crop yield (ton/ha). The volume of water used to grow crops in the field has two components: effective rainfall (green water) and irrigation water (blue water). The CROPWAT model (FAO, 2003a; Allen et al., 1998) has been used to estimate the effective rainfall and the irrigation requirements per country. The climate data have been taken from FAO (2003b,c) for the most appropriate climatic stations (USDA/NOAA, 2005a) located in the major cotton producing regions of each country. The actual irrigation water use is taken equal to the irrigation requirements as estimated with the CROPWAT model for those countries where the whole harvesting area is reportedly irrigated. In the countries where only a certain fraction of the harvesting area is irrigated, the actual irrigation water use is taken equal to this fraction times the irrigation water requirements.

The 'green' virtual water content of the crop (V_g) has been estimated as the ratio of the effective rainfall (P_e) to the crop yield (Y) (Eq. (1)). The 'blue' virtual water content of the crop

Table 1 – The top-15 of seed cotton producing countries

Countries	Average production (ton/year)*	% contribution to global production*	Planting period**	Yield (ton/ha)*
China	13,604,100	25.0	April/May	3.16
USA	9,699,662	17.8	March/May	1.86
India	5,544,380	10.2	April/May/July	0.62
Pakistan	5,159,839	9.5	May/June	1.73
Uzbekistan	3,342,380	6.1	April	2.24
Turkey	2,199,990	4.0	April/May	3.12
Australia	1,777,240	3.3	October/November	3.74
Brazil	1,613,193	3.0	October	2.06
Greece	1,253,288	2.3	April	3.02
Syria	1,016,594	1.9	April/May	3.92
Turkmenistan	954,440	1.8	March/April	1.72
Argentina	712,417	1.3	October/December	1.16
Egypt	710,259	1.3	February/April	2.39
Mali	463,043	0.9	May/July	1.03
Mexico	453,788	0.8	April	2.98
Others	5,939,363	10.9	–	–
World	54,443,977	100	–	–

Period 1997–2001.
* Source: FAOSTAT (2004).
** Sources: UNCTAD (2005a), FAO (2005), Cotton Australia (2005).

(V_b) has been taken equal to the ratio of the volume of irrigation water used (*I*) to the crop yield (*Y*) (Eq. (2)).

$$V_g = \frac{P_e}{Y} \quad (1)$$

$$V_b = \frac{I}{Y} \quad (2)$$

The total virtual water content of seed cotton is the sum of the green and blue components, calculated separately for the 15 largest cotton-producing countries. These countries contribute nearly 90% of the global cotton production (Table 1). For the remaining countries the global average virtual water content of seed cotton has been assumed. In the 15 largest cotton-producing countries, the major cotton-producing regions have been identified (Table 2) so that the appropriate climate data could be selected. For regions with more than one climate station, the data for the relevant stations have been equally weighed assuming that the stations represent equally sized cotton-producing areas. National average crop water requirements have been calculated on the basis of the respective share of each region to the national production.

The calculated national average crop water requirements for the 15 largest cotton-producing countries are presented in Table 3. Total volumes of water use and the average virtual water content of seed cotton for the major cotton-producing countries are presented in Table 4. The global average virtual water content of seed cotton is 3644 m^3/ton. The global volume of water use for cotton crop production is 198 Gm^3/year with nearly an equal share of green and blue water.

The water use for cotton production differs considerably over the countries. Climatic conditions for cotton production are least attractive in Syria, Egypt, Turkmenistan, Uzbekistan and Turkey because evaporative demand in all these countries is very high (1000–1300 mm) while effective rainfall is very low (0–100 mm). The shortage of rain in these countries has been solved by irrigating the full harvesting area. Resulting yields

Table 2 – Main regions of cotton production within the major cotton producing countries

Country	Major cotton harvesting regions and their share to the national harvesting area*
Argentina	Chaco (85%)
Australia	Queensland (23%) and New Southwales (77%)
Brazil	Parana (43%), Sao Paulo (21%), Bahia (8%), Minas Gerais (5%), Mato Grosso (5%), Goias (4%) and Mato Gross do Sul (4%)
China	Xinjiang (21.5%), Henan (16.6%), Jiangsu (11.5%), Hubei (11.4%), Shandong (10%), Hebei (6.7%), Anhui (6.4%), Hunan (5.2%), Jiangxi (3.3%), Sichuan (2.3%), Shanxi (1.7%), and Zhejiang (1.3%)
Egypt	Cairo (85%)
Greece	C. Macedonia (14%), E. Macedonia (27%), and Thessaly (51%)
India	Punjab (18%), Andhra Pradesh (14%), Gujarat (14%), Maharastha (13%), Haryana (10%), Madhya Pradesh (10%), Rajasthan (8%), Karnataka (8%), and Tamil Nadu (4%)
Mali	Segou (85%)
Mexico	Baja California, Chihuahua and Coahuila
Pakistan	Sindh (15%) and Punjab (85%)
Syria	Al Hasakah (33%), Ar Raqqah (33%) and Dayr az Zawr (33%)
Turkey	Aegean/Izmir (33.6%), Antalya (1.2%), Cukurova (20.2%) and Southeasten Anotolia (45%)
Turkmenistan	Ahal (85%)
USA	North Carolina (5.4%), Missouri, Mississippi, W. Tennessee, E. Arkansas, Louisiana, Georgia (Macon) (27.7%), Georgia (Macon) (9.6%), E. Texas (33.7%) and California, Arizona (14.3%)
Uzbekistan	Fergana (85%)

* Source: USDA/NOAA (2005b).

Table 3 – Consumptive water use at field level for cotton production in the major cotton producing countries

	Crop water requirement (mm)	Effective rainfall (mm)	Blue water requirement (mm)	Irrigated share of area* (%)	Consumptive water use		
					Blue water (mm)	Green water (mm)	Total (mm)
Argentina	877	615	263	100	263	615	877
Australia	901	322	579	90	521	322	843
Brazil	606	542	65	15	10	542	551
China	718	397	320	75	240	397	638
Egypt	1009	0	1009	100	1009	0	1009
Greece	707	160	547	100	547	160	707
India	810	405	405	33	134	405	538
Mali	993	387	606	25	151	387	538
Mexico	771	253	518	95	492	253	746
Pakistan	850	182	668	100	668	182	850
Syria	1309	34	1275	100	1275	34	1309
Turkey	963	90	874	100	874	90	963
Turkmenistan	1025	69	956	100	956	69	1025
USA	516	311	205	52	107	311	419
Uzbekistan	999	19	981	100	981	19	999

* Sources: Gillham et al. (1995), FAO (1999), Cotton Australia (2005), CCI (2005), WWF (1999).

vary from world-average (Turkmenistan) to very high (Syria, Turkey). Climatic conditions for cotton production are most attractive in the USA and Brazil. Evaporative demand is low (500–600 mm), so that vast areas can suffice without irrigation. Yields are a bit above world-average. India and Mali take a particular position by producing cotton under high evaporative water demand (800–1000 mm), short-falling effective rainfall (400 mm), and partial irrigation only (between a quarter and a third of the harvesting area), resulting in relatively low overall yields.

The average virtual water content of seed cotton in the various countries gives a first rough indication of the relative impacts of the various production systems on water. Cotton from India, Argentina, Turkmenistan, Mali, Pakistan, Uzbekistan, and Egypt is most water-intensive. Cotton from China and the USA on the other hand is very water-extensive. Since blue water generally has a much larger opportunity cost than green water, it makes sense to particularly look at the blue virtual water content of cotton in the various countries. China and the USA then still show a positive picture in this comparative analysis. Also Brazil comes in a positive light now, due to the acceptable yields under largely rain-fed conditions. The blue virtual water content and thus the impact per unit of cotton production are highest in Turkmenistan, Uzbekistan, Egypt, and Pakistan, followed by Syria, Turkey, Argentina and India.

It is interesting to compare neighbouring countries such as Brazil–Argentina and India–Pakistan. Cotton from Brazil is preferable over cotton from Argentina from a water resources point of view because growth conditions are better in Brazil

Table 4 – Volume of water use and virtual water content of seed cotton

	Volume of water use (Gm^3/year)			Seed cotton production (ton/year)	Virtual water content (m^3/ton)		
	Blue	Green	Total		Blue	Green	Total
Argentina	1.6	3.8	5.5	712,417	2307	5394	7700
Australia	2.5	1.5	4	1,777,240	1408	870	2278
Brazil	0.1	4.2	4.2	1,613,193	46	2575	2621
China	10.3	17.1	27.5	13,604,100	760	1258	2018
Egypt	3	0	3	710,259	4231	0	4231
Greece	2.3	0.7	2.9	1,253,288	1808	530	2338
India	11.9	36.1	48	5,544,380	2150	6512	8662
Mali	0.7	1.7	2.4	463,043	1468	3750	5218
Mexico	0.8	0.4	1.1	453,788	1655	852	2508
Pakistan	19.9	5.4	25.4	5,159,839	3860	1054	4914
Syria	3.3	0.1	3.4	1,016,594	3252	88	3339
Turkey	6.2	0.6	6.8	2,199,990	2812	288	3100
Turkmenistan	5.3	0.4	5.7	954,440	5602	407	6010
USA	5.6	16.2	21.8	9,699,662	576	1673	2249
Uzbekistan	14.6	0.3	14.9	3,342,380	4377	83	4460
Sub-total	88.2	88.6	176.8	48,504,613	–	–	–
Average	–	–	–	–	1818	1827	3644
Other countries	10.8	10.8	21.6	5,939,363	–	–	–
World	99.0	99.4	198.4	54,443,977	–	–	–

Period: 1997–2001.

(smaller irrigation requirements) and even despite the fact that the cotton harvesting area in Argentina is fully irrigated (compared to 15% in Brazil), the yields in Argentina are only half the yield in Brazil. Similarly, cotton from India is to be preferred over cotton from Pakistan–again from a water resources point of view only–because the effective rainfall in Pakistan's cotton harvesting area is low compared to that in India and the harvesting area in Pakistan is fully irrigated. Although India achieves very low cotton yields per hectare, the blue water requirements per ton of product are much lower in India compared to Pakistan.

5. The virtual water content of cotton products

The different processing steps that transform the cotton plant through various intermediate products to some final products are shown in Fig. 2. The virtual water content of seed cotton is attributed to its products following the methodology as introduced and applied by Chapagain and Hoekstra (2004). That means that the virtual water content of each processed cotton product has been calculated based on the product fraction (ton of crop product obtained per ton of primary crop) and the value fraction (the market value of the crop product divided by the aggregated market value of all crop products derived from one primary crop). The product fractions have been taken from the commodity trees in FAO (2003d) and UNCTAD (2005b). The value fractions have been calculated based on the market prices of the various products. The global average market prices of the cotton products have been calculated from ITC (2004). In calculating the virtual water content of fabric, the process water requirements for bleaching, dying and printing have been added (30 m^3 per ton for bleaching, 140 m^3 per ton for dying and 190 m^3 per ton for printing). In the step of finishing there is also additional water required (140 m^3/ton). The process water requirements have to be understood as rough average estimates, because the actual water requirements vary considerably among various techniques used (Ren, 2000).

The green and blue virtual water content of different cotton products for the major cotton producing countries is presented in Table 5. These water volumes do not yet include the volume of water necessary to dilute the fertiliser-enriched return flows from the cotton plantations and the polluted return flows from the processing industries.

6. Impact on the water quality in the cotton producing countries

6.1. *Impact in the crop production stage*

Cotton production affects water quality both in the stage of growing and the stage of processing. The impact in the first

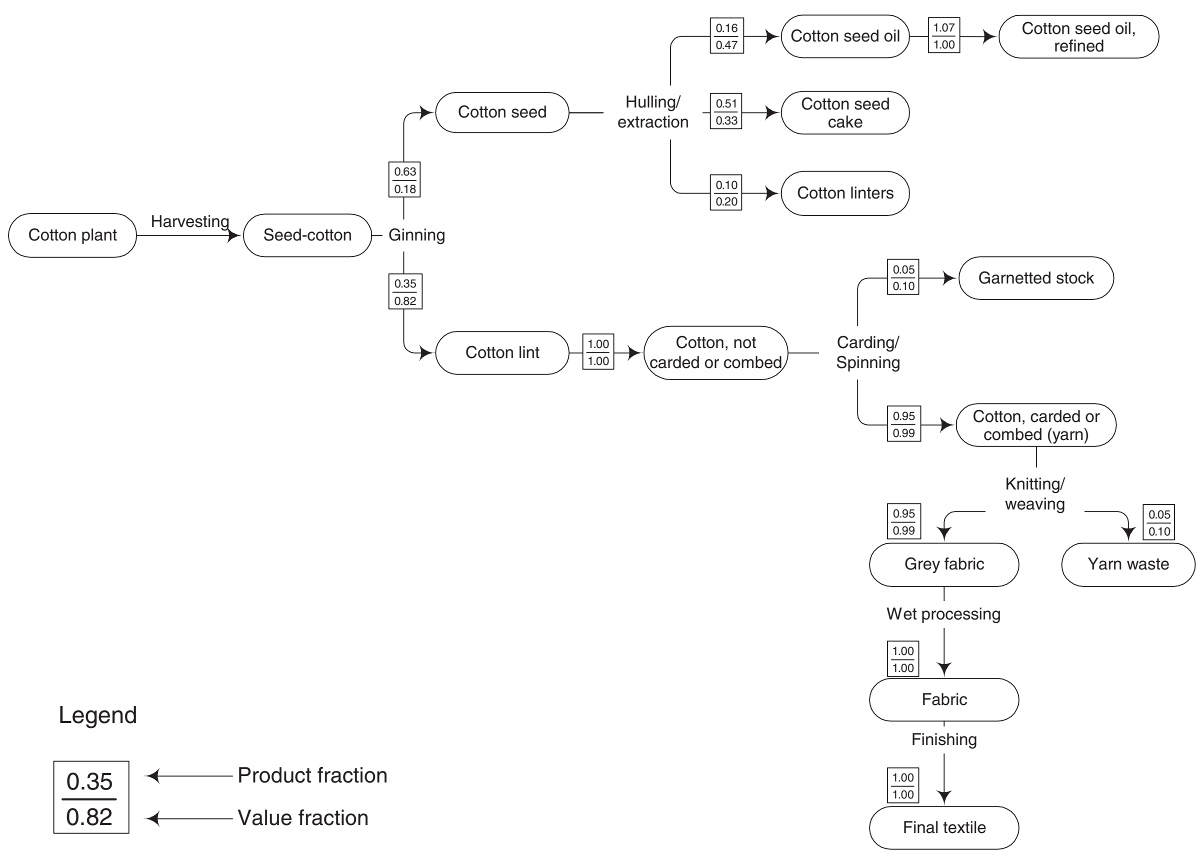

Fig. 2 – The product tree for cotton, showing the product fraction and value fraction per processing step.

Table 5 – Virtual water content of cotton products at different stages of production for the major cotton producing countries (m^3/ton)

	Cotton lint		Grey fabric		Fabric		Final textile		
	Blue	Green	Blue	Green	Blue	Green	Blue	Green	Total
Argentina	5385	12,589	5611	13,118	5971	13,118	6107	13,118	19225
Australia	3287	2031	3425	2116	3785	2116	3921	2116	6037
Brazil	107	6010	112	6263	472	6263	608	6263	6870
China	1775	2935	1849	3059	2209	3059	2345	3059	5404
Egypt	9876	0	10,291	0	10,651	0	10,787	0	10787
Greece	4221	1237	4398	1289	4758	1289	4894	1289	6183
India	5019	15,198	5230	15,837	5590	15,837	5726	15,837	21563
Mali	3427	8752	3571	9120	3931	9120	4067	9120	13188
Mexico	3863	1990	4026	2073	4386	2073	4522	2073	6595
Pakistan	9009	2460	9388	2563	9748	2563	9884	2563	12447
Syria	7590	204	7909	213	8269	213	8405	213	8618
Turkey	6564	672	6840	701	7200	701	7336	701	8037
Turkmenistan	13,077	951	13,626	991	13,986	991	14,122	991	15112
USA	1345	3906	1401	4070	1761	4070	1897	4070	5967
Uzbekistan	10,215	195	10,644	203	11,004	203	11,140	203	11343
Global average	4242	4264	4421	4443	4781	4443	4917	4443	9359

stage depends upon the volumes of nutrients (nitrogen, phosphorus, potash and other minor nutrients) and pesticides that leach out of the plant root zone, thus contaminating groundwater and surface water. In some cases, accumulation of chemicals in the soil (phosphorus) or the food chain (pesticides) is of concern as well. Most of the pesticides applied get into either ground water or surface water bodies. Only 2.4% of the world's arable land is planted with cotton, yet cotton accounts for 24% of the world's insecticide market and 11% of the sale of global pesticides (WWF, 2003). N-fertiliser added to the field is partly taken up by the plant, is partly transformed through denitrification into N_2 that leaves the soil to the atmosphere and partly leaches to the groundwater or gets washed away through surface runoff. In water bodies, high nitrogen concentrations can lead to problems of algae growth and increased cost of purification in case of water use for drinking.

About 60% of the total nitrogen applied is removed from the field in the form of harvested seed cotton (CRC, 2004). Silvertooth et al. (2001) approximate that out of the total nitrogen applied about 20% leaves the field through leaching to the groundwater, surface runoff or denitrification to the atmosphere. In the present study, the quantity of N that reaches free flowing water bodies is assumed to be 10% of the

Table 6 – Fertilizer application and the volume of water required to dilute the fertilizers leached to the water bodies

Countries	Average fertilizer application rate* (kg/ha)			Total fertilizer applied (ton/year)			Nitrogen leached to the water bodies	Volume of dilution water required	
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	(ton/year)	(10^6 m^3/year)	(m^3/ton)
Argentina	40	5		25,009	3126		2501	250	351
Australia	121	20	12.4	58,087	9601	5953	5809	581	327
Brazil	40	50	50	30,674	38,342	38,342	3067	307	190
China	120	70	25	516,637	301,372	107,633	51,664	5166	380
Egypt	54	57	57	16,076	16,969	16,969	1608	161	226
Greece	127	39	3.5	52,630	16,162	1450	5263	526	420
India	66	28	6	588,675	249,741	53,516	58,868	5887	1062
Mali	35			15,710			1571	157	339
Mexico	120	30		18,315	4579		1831	183	404
Pakistan	180	28	0.4	536,720	83,490	1193	53,672	5367	1040
Syria	50	50		12,964	12,964		1296	130	128
Turkey	127	39	3.5	89,927	27,615	2,478	8993	899	409
Turkmenistan	210	45	1.2	117,495	25,178	671	11,750	1175	1,231
USA	120	60	85	625,544	312,772	443,094	62,554	6255	645
Uzbekistan	210	45	1.2	313,274	67,130	1,790	31,327	3133	937
Average**	91	35	20						622
Sum				3,017,737	1,169,041	673,090	301,774	30,177	

Period: 1997–2001.

* Source: IFA et al. (2002). For Uzbekistan, Mali and Turkey, the fertiliser application rate has been taken from Turkmenistan, Nigeria and Greece respectively.

** The global average fertilizer application rate has been calculated from the country-specific rates, weighted on the basis of the share of a country in the global area of cotton production.

Table 7 – Waste water characteristics at different stages of processing cotton textiles and permissible limits to discharge into water bodies

Process	Waste water volume* (m^3/ton)	Pollutants** (kg/ton)			
		BOD	COD	TSS	TDS
Wet processing	360	32	123	25	243
Bleaching	30	5	13		28
Dying	142	6	24		180
Printing	188	21	86	25	35
Finishing	136	6	25	12	17
Total	496	38	148	37	260
Permissible limits (mg/l)***		50	250	50	

* Source: USEPA (1996).
** Source: UNEP IE (1996).
*** Source: WB (1999).

applied rate assuming a steady state balance at root zone in the long run. The effect of the use of other nutrients, pesticides and herbicides in cotton farming to the environment has not been analysed.

The total volume of water required per ton N is calculated considering the volume of nitrogen leached (ton/ton) and the permissible limit (ton/m^3) in the free flowing surface water bodies. The standard recommended by EPA (2005) for nitrate in drinking water is 10 mg/l (measured as nitrogen) and has been taken to calculate the necessary dilution water volume. This is a conservative approach, since natural background concentration of N in the water used for dilution has been assumed negligible.

We have used the average rate of fertiliser application for the year 1998 as reported by IFA et al. (2002). The total volume of fertilizer applied is calculated based on the average area of cotton harvesting for the concerned period (Table 6).

6.2. *Impact in the processing stage*

The average volumes of water use in wet processing (bleaching, dying and printing) and finishing stage are 360 m^3/ton and 136 m^3/ton of cotton textile respectively (USEPA, 1996). The biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and the total dissolved solids (TDS) in the effluent from a typical textile industry are given by UNEP IE (1996) and presented in Table 7. In this study, the maximum permissible limits for effluents to discharge into surface and ground water bodies are taken from the guidelines set by the World Bank (1999).

As the maximum limits for different pollutants are different, the volume of water required to meet the desired level of dilution will be different per pollutant category in each production stage. Per production stage, the pollutant category that requires most dilution water has been taken as indicative for the total dilution water requirement (Table 8).

The virtual water content of a few specific consumer products is shown in Table 9.

Table 8 – Volume of water necessary to dilute pollution per production stage

Stage of production	Volume of water per pollutant category(m^3/ton of cotton textile)			Dilution water volume (applicable) (m^3/ton)
	BOD	COD	TSS	
Wet processing	640	492	500	640
Finishing	120	100	240	240
Wet processing and finishing carried at the same place	760	592	740	760
Wet processing and finishing carried at different place	–	–	–	880

Table 9 – Global average virtual water content of some selected consumer products

	Standard weight (g)	Virtual water content (l)			
		Blue water	Green water	Dilution water	Total volume of water
1 pair of Jeans	1000	4900	4450	1500	10,850
1 Single bed sheets	900	4400	4000	1350	9750
1 T-shirt	250	1230	1110	380	2720
1 Diaper	75	370	330	110	810
1 Johnson's cotton bud	0.333	1.6	1.5	0.5	3.6

7. International virtual water flows

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

$$F[n_e, n_i, c] = T[n_e, n_i, c] \times V_t[n_e, c] \quad (3)$$

in which F denotes the virtual water flow (m^3/year) from exporting country n_e to importing country n_i as a result of trade in cotton product c; T the commodity trade (ton/year) from the exporting to the importing country; and V_t the total virtual water content (m^3/ton) of the commodity in the exporting country. We have taken into account the international trade of cotton products for the complete set of countries from 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 for the period 1997–2001 (ITC, 2004).

For the calculation of international virtual water flows, all cotton products are considered as reported in the database of ITC (2004). It includes the complete set of cotton products from the commodity groups 12, 14, 15, 23, 60, 61, 62 and 63. From group 52, only those products with more than 85% of cotton in their composition are considered.

The calculated virtual water flows between countries in relation to the international trade in cotton products add up to 204 Gm^3/year at a global scale (an average for the period 1997–2001). About 43% of this total flow refers to blue water, about 40% to green water and about 17% to dilution water (Tables 10

Table 10 – Gross virtual water export from the major cotton producing countries related to export of cotton products

	Green water (Gm^3/year)	Blue water (Gm^3/year)	Dilution water (Gm^3/year)	Total (Gm^3/year)	Contribution to the global flows (%)
Argentina	1.98	0.85	0.13	2.95	1
Australia	1.44	2.34	0.55	4.34	2
Brazil	1.03	0.07	0.17	1.27	1
China	11.36	9.32	5.43	26.11	13
Egypt	–	1.72	0.13	1.85	1
Greece	0.41	1.41	0.36	2.18	1
India	16.83	5.75	3.08	25.66	13
Mali	1.17	0.46	0.11	1.73	1
Mexico	1.04	2.23	0.86	4.13	2
Pakistan	2.87	10.64	3.05	16.56	8
Syria	0.04	1.63	0.07	1.75	1
Turkey	0.40	4.08	0.89	5.37	3
Turkmenistan	0.10	1.41	0.31	1.83	1
Uzbekistan	0.15	7.74	1.66	9.55	5
USA	11.18	4.34	5.18	20.70	10
Others	31.06	32.73	13.83	77.62	38
Global flows	81.05	86.72	35.83	203.6	

Period: 1997–2001.

and 11). The virtual water flows in relation to international trade in all crop, livestock and industrial products add up to 1625 Gm^3/year at a global scale (Chapagain and Hoekstra, 2004). The global sum of annual gross virtual water flows between nations related to cotton trade is thus 12% of the total sum of international virtual water flows.

The countries producing more than 90% of seed cotton are responsible for only 62% of the global virtual water exports (Table 10). This can be understood from the fact that the countries that import the raw cotton from the major producing countries export significant volumes again to other countries, often in some processed form. Export of cotton products made from imported raw cotton is significant for instance in Japan, the European Union, and Canada.

Pakistan, China, Uzbekistan and India are the largest exporters of blue water. These countries export a lot of water in absolute sense, but in relative sense as well: more than half of the blue water used for cotton irrigation enters export products. The USA also appears in the top-list of total virtual water exporters due to its large share of green water export. The largest gross dilution volume exporters are China, USA and Pakistan, implying that the international trade in cotton products is having larger impact on the water quality in these countries.

8. Water footprints related to consumption of cotton products

In assessing a national water footprint due to domestic cotton consumption we distinguish between the internal and the external footprint. The internal water footprint is defined as

Table 11 – Largest gross virtual water importers related to the international trade of cotton products

	Green water (Gm^3/year)	Blue water (Gm^3/year)	Dilution water (Gm^3/year)	Total (Gm^3/year)	Contribution to the global flows (%)
Brazil	2	1.5	0.4	3.9	2
Canada	1.6	1	0.6	3.2	2
China	15.6	15.9	6.7	38.2	19
France	2.4	3.2	1.2	6.8	3
Germany	3.5	5	1.8	10.4	5
Indonesia	1.9	2	0.7	4.6	2
Italy	2.9	4.5	1.3	8.7	4
Japan	3.3	3.3	1.5	8.2	4
Korea Rep.	2.6	2.8	1	6.4	3
Mexico	6.4	2.9	3.2	12.5	6
Netherlands	1.4	1.6	0.7	3.7	2
Russian federation	0.5	2.5	0.6	3.7	2
Thailand	1.5	1.4	0.5	3.3	2
Turkey	1.4	2.6	0.7	4.7	2
UK	2.9	3.1	1.3	7.3	4
USA	10	12.2	5.3	27.5	14
Others	21.2	21.1	8.3	50.6	25
Global flows	81.05	86.72	35.83	203.6	

Period: 1997–2001.

the use of domestic water resources to produce cotton products consumed by inhabitants of the country. It is the sum of the total volume of water used from the domestic water resources to produce cotton products minus the total volume of virtual water export related to export of domestically produced cotton products. The external water footprint of a country is defined as the annual volume of water resources used in other countries to produce cotton products consumed by the inhabitants of the country concerned. The external water footprint is calculated by taking the total virtual water import into the country and subtracting the volume of virtual water exported to other countries as a result of re-export of imported products.

The global water footprint related to the consumption of cotton products is estimated at 256 Gm^3/year, which is 43 m^3/year per capita in average. About 42% of this footprint is due to the use of blue water, another 39% to the use of green water and about 19% to the dilution water requirements (Table 12). About 44% of the global water use for cotton growth and processing is not for serving the domestic market but for export. If we do not consider the water requirements for cotton products only, but take into account the water needs for the full scope of consumed goods and services, the global water footprint is 7450×10^9 m^3/year (Chapagain and Hoekstra, 2004). This includes the use of green and blue water for the full spectrum of the global consumption goods and services, but it excludes the water requirement for dilution of waste flows. As a proxy for the latter we take here the rough estimate provided by Postel et al. (1996), who estimate the global dilution water requirement at 2350×10^9 m^3/year. This means that the full global water footprint is about 9800×10^9 m^3/year. The global water footprint related to cotton consumption is 256×10^9 m^3/year, which means that the consumption of cotton products takes a share of 2.6% of the full global water footprint.

The countries with the largest impact on the foreign water resources are China, USA, Mexico, Germany, UK, France, and Japan (Table 13). About half of China's water footprint due to cotton consumption is within China (the internal water footprint); the other half (the external footprint) presses in other countries, mainly in India (dominantly green water use) and Pakistan (dominantly blue water use).

Per country, the water footprint as a result of domestic cotton consumption can be mapped as has been done for the USA in Fig. 3. The arrows show the tele-connections between the area of consumption (the USA) and the areas of impact (notably India, Pakistan, China, Mexico and Dominican Republic). The total water footprint of an average US citizen due to the consumption of cotton products is 135 m^3/year–more than three times the global average–out of which about half is from the use of external water resources. If all world citizens would consume cotton products at the US rate, other factors remaining equal, the global water use would increase by 5% [from 9800 to 10300 Gm^3/year], which is quite substantial given that humanity already uses more than half of the runoff water that is reasonably accessible (Postel et al., 1996).

For proper understanding of the impact map shown in Fig. 3, it should be observed here that the map shows the full internal water footprint of the USA plus the external water footprints in other countries insofar easily traceable. For instance, USA imports several types of cotton products from the EU, that together contain 430 million m^3/year of virtual water, but these cotton products do not fully originate from the EU25. In fact, the EU25 imports raw cotton, grey fabrics and final products from countries such as India, Uzbekistan and Pakistan, then partly or fully processes these products into final products and ultimately exports to the USA. Out of the 430 million m^3/year of virtual water exported from the EU25 to the USA, only 16% is actually water appropriated within the EU25; the other 84% refers to water use in countries from which the EU25 imports (e.g. India, Uzbekistan, Pakistan). For simplicity, we show in the map only the 'direct' external footprints (tracing the origin of imported products only one step back), and not the 'indirect' external footprints. Adding the latter would mean adding for instance an arrow from India to EU25, which then is forwarded to the USA. Doing so for all indirect external water footprints would create an incomprehensible map. For the same reason, we have shown only arrows for the largest virtual water flows towards the USA.

The water footprint as a result of cotton consumption in Japan is mapped in Fig. 4. For their cotton the Japanese consumers most importantly rely on the water resources of China, Pakistan, India, Australia and the USA. Japan does not grow cotton, and also does not have a large cotton processing industry. The Japanese water footprint due to consumption of cotton products is 4.6 Gm^3/year, of which 95% presses in other countries. The cotton products imported from Pakistan put a large pressure on Pakistan's scarce blue water resources. In China and even more so in India, cotton is produced with lower inputs of blue water (in relation to the green water inputs), so that cotton products from China and India put less

Table 12 – The global water footprint due to cotton consumption (Gm^3/year)

	Blue water footprint	Green water footprint	Dilution water footprint	Total water footprint	Contribution to the total water footprint
Internal water footprint *	59.6	54.8	28.5	143	56%
External water footprint *	48.0	44.7	20.7	113	44%
Total water footprint	108	99	49	256	
Contribution to the total water footprint	42%	39%	19%		

Period: 1997–2001.
* The internal water footprint at global scale refers to the aggregated internal water footprints of all nations of the world. The external water footprint refers here to the aggregated external water footprints of all nations.

Table 13 – The composition, per country, of the water footprint related to the consumption of cotton products

	Internal water footprint (Mm³/year)				External water footprint (Mm³/year)				Total (Mm³/year)
	Blue	Green	Dilution	Total	Blue	Green	Dilution	Total	
Albania	1	0	1	3	27	16	10	52	55
Algeria	7	0	13	20	133	63	33	229	249
Angola	21	19	10	51	0	0	0	0	51
Argentina	832	1953	156	2940	22	89	20	131	3071
Australia	755	585	296	1637	234	294	164	691	2328
Austria	6	0	11	17	395	169	133	696	713
Azerbaijan	46	34	30	110	2	1	1	3	113
Bahamas	1	0	1	1	9	20	11	40	41
Bangladesh	4	29	44	77	20	587	79	687	764
Barbados	0	0	0	0	1	3	1	6	6
Belarus	8	0	14	22	144	32	37	213	234
Belgium–Luxembourg	15	0	25	41	1215	763	395	2373	2414
Benin	200	209	85	494	10	19	6	36	530
Bhutan	0	0	0	0	2	6	1	9	9
Bolivia	83	98	45	227	74	502	105	681	908
Botswana	7	5	5	16	25	26	10	60	77
Brazil	404	3454	804	4662	1451	1643	369	3464	8126
Brunei	2	0	3	5	58	59	29	146	151
Burkina Faso	284	258	136	679	0	0	0	0	679
Burundi	4	4	2	10	1	2	1	3	13
Cameroon	88	85	37	211	1	1	0	2	213
Canada	39	0	86	125	592	1204	478	2274	2399
Central African Rep.	18	17	8	43	0	0	0	0	43
Chad	123	118	50	291	0	0	0	0	291
Chile	8	0	14	22	134	302	50	486	507
China	8775	11,176	6585	26,536	10,738	10,213	4485	25,436	51,972
Colombia	174	160	115	449	170	357	98	625	1074
Congo, DR	56	50	28	134	0	0	0	0	134
Côte d'Ivoire	189	198	74	462	5	12	2	20	481
Croatia	2	0	3	5	59	43	18	120	125
Cyprus	0	0	1	1	23	21	10	55	55
Czech Republic	15	0	23	38	392	113	104	609	647
Denmark	5	0	9	14	221	207	96	524	538
Ecuador	15	12	15	42	29	60	25	115	157
Egypt	1433	0	177	1610	60	193	25	278	1888
Equatorial Guinea	8	0	14	22	0	0	0	0	22
Estonia	7	0	12	19	307	49	81	437	455
Ethiopia	79	74	35	189	4	3	2	8	197
Finland	0	0	1	1	67	70	31	167	168
France	53	0	93	146	2387	1576	867	4831	4977
Gambia	2	1	2	4	9	14	4	28	32
Germany	47	0	79	126	3525	2049	1220	6794	6920
Ghana	45	41	23	109	9	10	4	24	133
Greece	1199	416	382	1997	278	266	115	660	2657
Guinea	74	69	37	180	17	26	11	54	234
Hungary	8	0	13	21	232	118	74	424	444
Iceland	0	0	0	0	5	5	2	12	12
India	7015	19,462	3965	30,441	281	222	81	583	31,024
Indonesia	86	18	152	256	773	683	330	1786	2042
Iran	789	731	353	1874	32	4	7	43	1917
Ireland	5	0	10	15	198	196	86	481	496
Israel	124	124	72	320	452	814	241	1508	1828
Italy	83	0	106	189	2254	644	465	3363	3552
Japan	78	0	165	244	1696	1735	935	4366	4610
Jordan	1	0	2	3	48	19	13	79	82
Kazakhstan	174	169	68	411	0	0	0	1	412
Kenya	26	29	12	67	23	45	11	79	146
Korea, DPR	64	59	30	153	0	0	0	0	153
Korea, Rep.	124	0	224	348	1808	1538	648	3994	4343
Kyrgyzstan	55	54	20	129	0	0	0	0	129
Laos	5	5	1	11	0	0	0	0	11
Lebanon	2	0	3	5	57	60	19	136	141

Table 13 (*continued*)

	Internal water footprint (Mm^3/year)				External water footprint (Mm^3/year)				Total (Mm^3/year)
	Blue	Green	Dilution	Total	Blue	Green	Dilution	Total	
Lithuania	1	0	2	3	31	22	10	63	66
Malawi	46	45	17	108	0	0	0	0	108
Malaysia	36	0	68	105	609	686	262	1557	1662
Maldives	2	0	4	7	84	229	47	361	368
Mali	241	573	80	894	1	1	1	3	897
Malta	2	0	3	4	56	28	15	99	103
Mauritius	10	0	21	31	117	456	59	632	663
Mexico	460	327	549	1336	1297	5395	2489	9181	10,517
Mozambique	50	46	23	119	0	0	0	0	119
Myanmar	228	214	100	542	0	0	0	0	542
Namibia	8	7	4	19	0	0	0	0	19
Nepal	3	1	4	8	39	181	26	245	253
Netherlands	22	0	39	61	1277	1035	539	2850	2912
New Zealand	4	0	7	12	157	147	74	378	389
Niger	12	10	7	29	5	5	2	12	41
Nigeria	658	613	311	1583	93	200	48	341	1924
Norway	2	0	3	5	157	148	73	378	383
Pakistan	9672	2567	3012	15,251	0	0	0	0	15,251
Papua New Guinea	0	0	0	0	7	6	3	15	16
Paraguay	147	156	55	358	3	10	2	15	373
Peru	138	145	78	361	64	130	32	226	587
Philippines	14	2	25	41	160	222	75	457	498
Poland	34	0	55	88	769	274	215	1258	1347
Portugal	39	0	54	93	449	235	102	787	880
Russian Federation	84	0	143	227	2076	74	496	2646	2874
Saudi Arabia	1	0	2	4	175	99	64	338	342
Senegal	15	21	8	44	5	15	3	23	67
Serbia and Montenegro	1	0	2	3	103	17	23	143	147
Singapore	17	0	31	47	708	857	361	1926	1974
Slovakia	4	0	6	9	81	34	25	140	150
Slovenia	2	0	3	6	87	36	23	146	152
South Africa	80	80	47	207	114	155	46	316	523
Spain	387	325	173	885	693	518	232	1443	2328
Sudan	209	208	75	492	2	1	1	4	496
Swaziland	39	34	20	93	16	16	7	39	132
Sweden	2	0	4	6	306	304	145	755	761
Switzerland	0	0	1	1	70	101	53	224	225
Syria	1736	45	166	1947	0	0	0	0	1947
Tajikistan	349	345	127	821	0	0	0	0	821
Tanzania	138	137	58	333	5	10	3	18	351
Thailand	106	42	136	285	690	766	243	1699	1984
Togo	123	120	54	297	12	15	6	32	330
Trinidad and Tobago	0	0	0	0	6	8	4	19	19
Turkey	3754	508	1172	5434	1453	1106	482	3042	8476
Turkmenistan	3958	287	897	5141	1	0	0	2	5143
Uganda	79	74	31	185	17	8	6	31	216
UK	35	0	62	97	2307	2175	980	5463	5560
Uruguay	0	0	1	1	9	36	4	50	51
USA	5111	9314	4971	19,397	9429	5738	3216	18,383	37,780
Uzbekistan	6956	131	1598	8685	0	0	0	0	8685
Venezuela	75	60	50	185	167	215	88	470	654
Yemen	42	39	19	100	0	0	0	0	100
Zambia	41	38	17	96	4	3	2	8	104
Zimbabwe	158	155	60	374	0	0	0	0	374
World	59,605	54,793	28,515	142,914	48,025	44,655	20,743	113,423	256,336

Period: 1997–2001.

stress per unit of cotton product on the scarce blue water resources than in Pakistan.

Fig. 5 shows the water footprint due to cotton consumption in the 25 countries of the European Union (EU25). 84% of EU's cotton-related water footprint lies outside the EU. From the map it can be seen that, for their cotton supply, the European community most heavily depends on the water resources of India. This puts stress on the water availability for other purposes in India. In India one-third of the cotton harvest area is being irrigated; particularly cotton imports from these

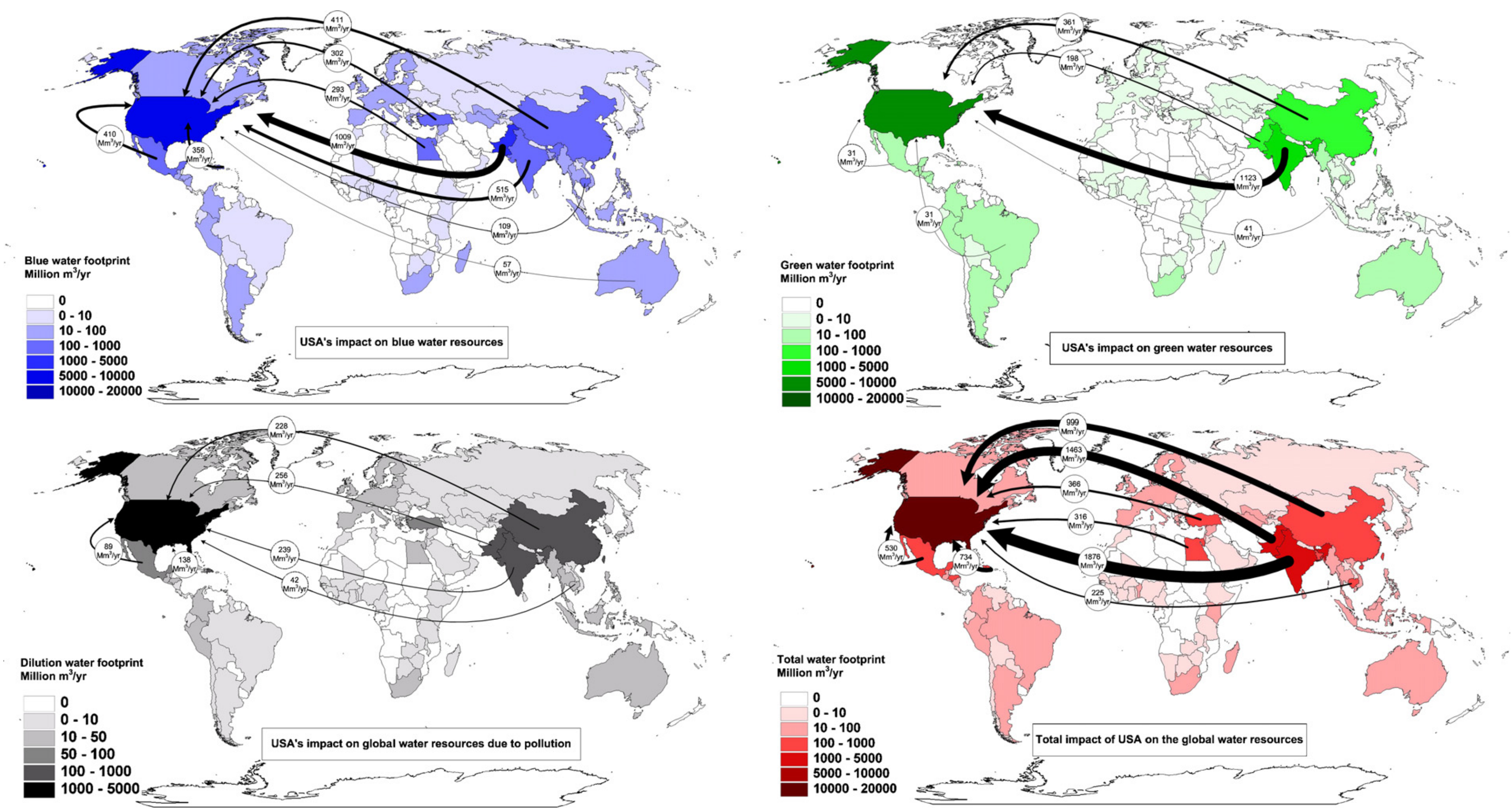

Fig. 3 – The impact of consumption of cotton products by US citizens on the world's water resources (Mm^3/year). Period: 1997–2001.

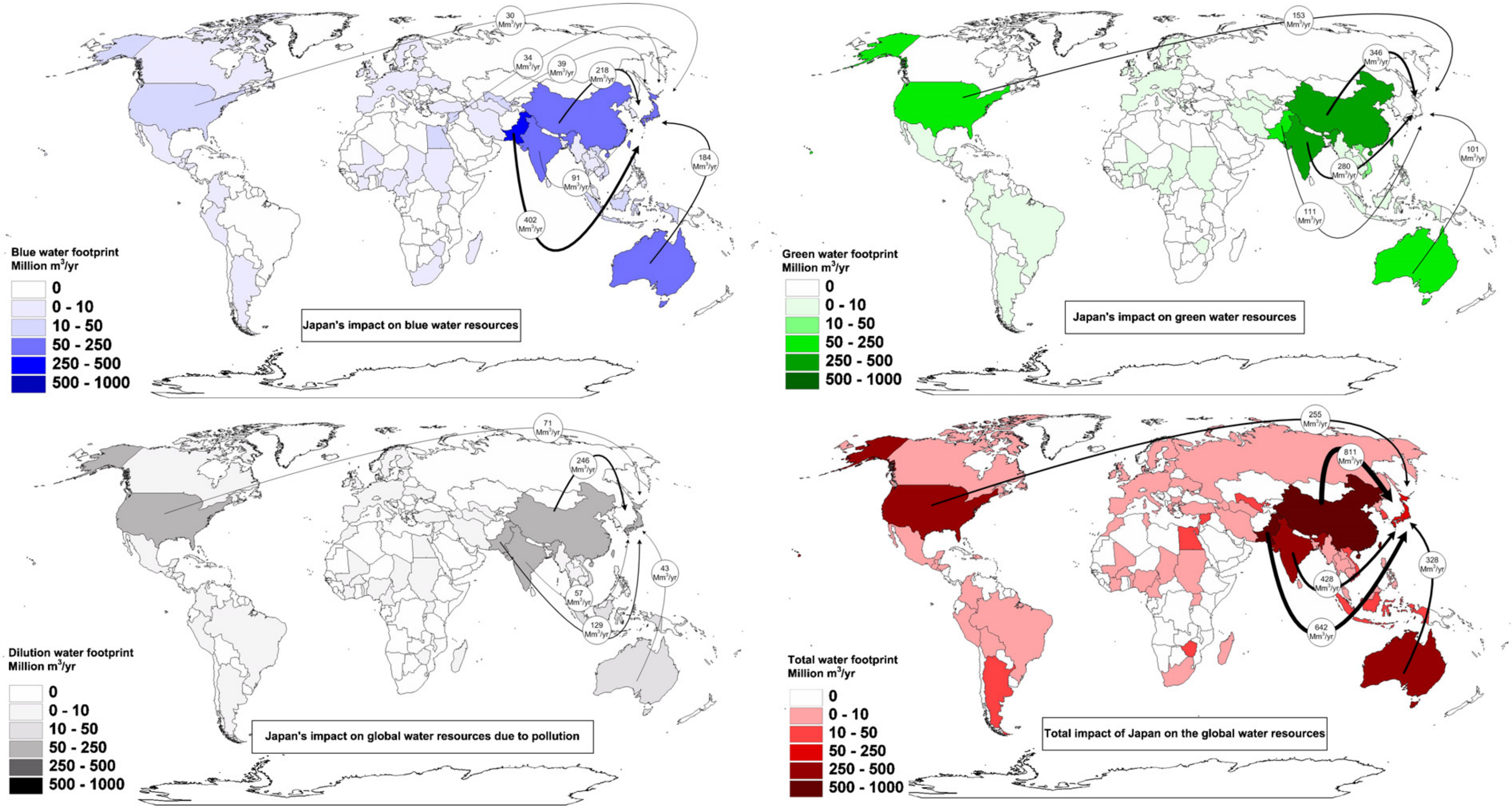

Fig. 4 – The impact of consumption of cotton products by Japanese citizens on the world's water resources (Mm^3/year). Period: 1997–2001.

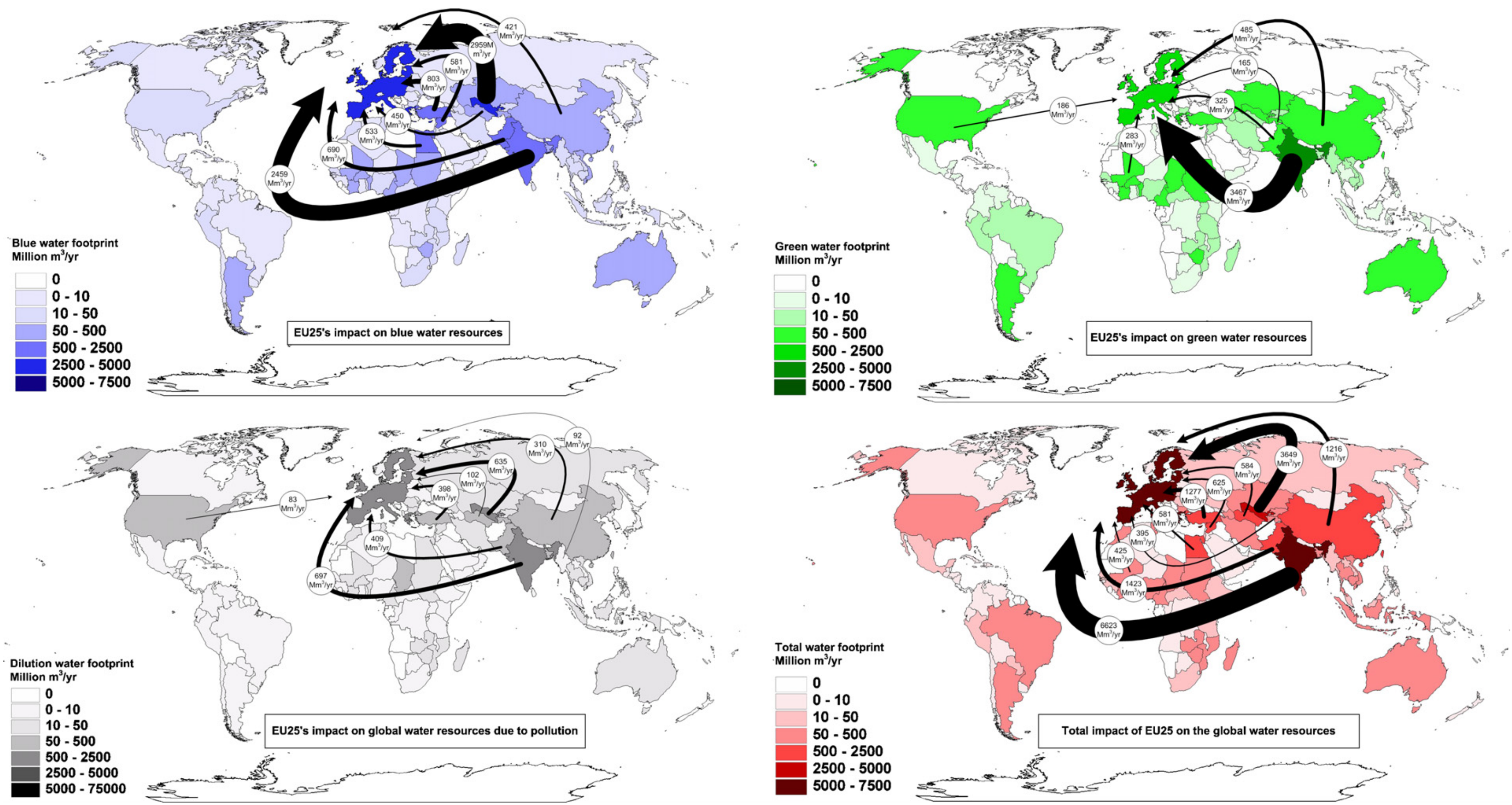

Fig. 5 – The impact of consumption of cotton products by the people in EU25 on the world's water resources (Mm^3/year). Period: 1997–2001.

irrigated areas have a large opportunity cost, because the competition for blue water resources is higher than for the green water resources. If we look at the impacts of European cotton consumption on blue water resources, the impacts are even higher in Uzbekistan than in India. Uzbekistan uses 14.6 Gm^3/year of blue water to irrigate cotton fields, out of which it exports 3.0 Gm^3/year in virtual form to the EU25. The consumers in the EU25 countries thus indirectly (and mostly unconsciously) contribute for about 20% to the desiccation of the Aral Sea. In terms of pollution, cotton consumption in the EU25 has largest impacts in India, Uzbekistan, Pakistan, Turkey and China. These impacts are partly due to the use of fertiliser in the cotton fields and partly to the use of chemicals in the cotton processing industries. Cotton consumption in the EU25 also causes pollution in the region itself, mainly from the processing of imported raw cotton or grey fabrics into final products.

The three components of a water footprint–green water use, blue water use and dilution water requirement–affect water systems in different ways. Use of blue water generally affects the environment more than green water use. Blue water is lost to the atmosphere where otherwise it would have stayed in the ground or river system where it was taken from. Green water on the other hand would have been evaporated through another crop or through natural vegetation if it would not have been used for cotton growth. Therefore there should generally be more concern with the 'blue water footprint' than with the 'green water footprint'. The part of the water footprint that refers to dilution water requirements deserves attention as well, since pollution is a choice and not necessary. Waste flows from cotton industries can be treated so that no dilution water would be required at all. An alternative to treatment of waste flows is reduction of waste flows. With cleaner production technology, the use of chemicals in cotton industries can be reduced by 30%, with a reduction of the COD content in the effluent of 60% (Visvanathan et al., 2000).

9. Conclusion

The authors believe that a single indicator of sustainability does not exist, because of the variety of facts, values and uncertainties that play a role in any debate of sustainable development. The water footprint of a nation should clearly not be seen as the ultimate indicator of sustainability, but rather as a new indicator that can add to the sustainability debate. It adds to the ecological footprint and the embodied energy concept by taking water as a central viewpoint as alternative to land or energy. It adds to earlier indicators of water use by taking the consumer's perspective on water use instead of the producer's perspective.

After the introduction of the ecological footprint concept in the 1990s, several scholars have expressed doubts whether the concept is useful in science or policy making. At the same time we see that the concept attracts attention and evokes scientific debate. We expect that the water footprint concept leads to a similar dual response. On the one hand the water footprint does not do else than gathering and presenting known data in a new format and as such does not add new knowledge. On the other hand, the water footprint adds a new fruitful perspective on issues such as water scarcity, water dependency, sustainable water use, and the implications of global trade for water management.

For water managers, water management is a river basin or catchment issue (see for instance the new South African National Water Act, 1998, and the new European Water Framework Directive, 2000). The water footprint, showing the use of water in foreign countries, shows that it is not sufficient to stick to that scale. Water problems in the major cotton producing areas of the world cannot be solved without addressing the global issue that consumers are not being held responsible for some of the economic costs and ecological impacts, which remain in the producing areas. The water footprint shows water use from the consumer's perspective, while traditional statistics show water use from the producer's perspective. This makes it possible to compare the water demand for North American or European citizens with the water demand for people in Africa, India or China. In the context of equitability and sustainability, this is a more useful comparison than a comparison between the actual water use in the USA or Europe with the actual water use in an African or Asian country, simply because the actual water use tells something about production but not about consumption.

The water footprint shows how dependent many nations are on the water resources in other countries. For its consumption of cotton products, the EU25 is very much dependent on the water resources in other continents, particularly water in Asia as this study shows, but also for other products there is a strong dependence on water resources outside Europe (Chapagain and Hoekstra, 2004). This means that water in Europe is scarcer than current indicators (showing water abstractions within Europe in relation to the available water resources within Europe) do suggest.

Cotton consumption is responsible for 2.6% of the global water use. As a global average, 44% of the water use for cotton growth and processing is not for serving the domestic market but for export. This means that–roughly spoken–nearly half of the water problems in the world related to cotton growth and processing can be attributed to foreign demand for cotton products. By looking at the trade relations, it is possible to track down the location of the water footprint of a community or, in other words, to link consumption at one place to the impacts at another place. The study for instance shows that the consumers in the EU25 countries indirectly contribute for about 20% to the desiccation of the Aral Sea. Visualizing the actual but hidden link between cotton consumers and the water impacts of cotton production is a relevant issue in the light of the fact that the economic and environmental externalities of water use are generally not included in the price of the cotton products paid by the foreign consumers. Including information about the water footprint in product information, be it in the form of pricing or product labelling, is thus a crucial aspect in policy aimed at the reduction of negative externalities as water depletion and pollution. Given the global character of the cotton market, international cooperation in setting the rules for cotton trade is a precondition.

Since each component of the total water footprint includes a certain economic cost and environmental impact, it would be useful to see which of the costs and impacts are transferred to the consumer. In this study we have not done a careful examination of that, but there is quite some evidence that the majority of costs and impacts of water use and pollution caused in agriculture and industry is not translated into the price of products. According to the World Bank, the economic cost recovery in developing countries in the water sector is about 25% (Serageldin, 1995). Social and environmental impacts of water use are generally not translated into the price of products at all, with sometimes an exception for the costs made for wastewater treatment before disposal. Most of the global waste flows are not treated however. Although a few industrialised countries achieve a wastewater treatment coverage of nearly 100%, this coverage remains below 5% in most developing countries (Eurostat, 2005; Hoekstra, 1998). Besides, the hundred percent waste coverage in some of the industrialised countries refers to treatment of concentrated waste flows from households and industries only, but excludes the diffuse waste flow in agriculture. Given the general lack of proper water pricing mechanisms or other ways of transmitting production-information, cotton consumers have little incentive to take responsibility for the impacts on remote water systems.

About one-fifth of the global water footprint due to cotton consumption is related to the pollution. This estimate is based on the assumption that wastewater flows can be translated into a certain water requirement for dilution based on water quality standards. Implicitly we have assumed here that the majority of waste flows enters natural water bodies without prior treatment, which is certainly true for leaching of fertilisers in agriculture and largely true for waste flows from cotton industries. In some of the rich countries, however, there is often treatment of waste flows from industries before disposal, so that we have got an overestimate of dilution water requirements here. In case of treatment of waste flows to the extent that the effluents meet water quality standards, a better estimate for the water requirement would be to consider the actual water use for the treatment process. Another issue is that we did not account for natural background concentrations in dilution water, so that we have got a conservative estimate for the required dilution volume. We also have made a conservative estimate by looking at the dilution volume required for fertilisers, but not at the volume for diluting pesticides used.

REFERENCES

Allan, J.A., 1997. 'Virtual water': a long term solution for water short Middle Eastern economies? Paper presented at the 1997 British Association Festival of Science, University of Leeds, 9 September 1997.

Allan, J.A., 1998. Virtual water: a strategic resource, global solutions to regional deficits. Groundwater 36 (4), 545–546.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper, vol. 56. Food and Agriculture Organization, Rome, Italy.

Chapagain, A.K., Hoekstra, A.Y., 2003a. Virtual Water Flows Between Nations in Relation to Trade in Livestock and Livestock Products. Value of Water Research Report Series, vol. 13. UNESCO-IHE, Delft, the Netherlands.

Chapagain, A.K., Hoekstra, A.Y., 2003b. The Water Needed to Have the Dutch Drink Coffee. Value of Water Research Report Series, vol. 14. UNESCO-IHE, Delft, the Netherlands.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water Footprints of Nations. Value of Water Research Report Series, vol. 16. UNESCO-IHE, Delft, the Netherlands.

Cotton Australia, 2005. How to Grow a Pair of Jeans. www.cottonaustralia.com.au.

CCI, 2005. Regions of US productions. Cotton Council International.

CRC, 2004. NUTRIpak: A Practical Guide to Cotton Nutrition. Australian Cotton Cooperative Research Centre.

De Man, R., 2001. The global cotton and textile chain: substance flows, actors and co-operation for sustainability. A study in the Framework of WWF's Freshwater and Cotton Programme. Reinier de Man Publications, Leiden, the Netherlands.

EPA, 2005. List of drinking water contaminants: ground water and drinking water. US Environmental Protection Agency.

Eurostat, 2005. http://epp.eurostat.cec.eu.int, EU Statistical Office, Luxembourg.

Falkenmark, M., 2003. Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges. Philos. Trans. R. Soc. Lond., B Biol. Sci. 358, 2037–2049.

FAO, 1999. Irrigation in Asia in Figures. Water Reports, vol. 18. Food and Agriculture Organization, Rome, Italy.

FAO, 2003a. CROPWAT Model. Food and Agriculture Organization, Rome, Italy.

FAO, 2003b. FAOCLIM: A CD-ROM with World-Wide Agroclimatic Data. Food and Agriculture Organization, Rome, Italy.

FAO, 2003c. CLIMWAT Database. Food and Agriculture Organization, Rome, Italy.

FAO, 2003d. Technical Conversion Factors for Agricultural Commodities. Food and Agriculture Organization, Rome, Italy.

FAO, 2005. Review of Global Agricultural Water Use Per Country, Crop Water Requirements. Food and Agriculture Organization, Rome, Italy.

FAOSTAT, 2004. http://faostat.fao.org, Food and Agriculture Organization, Rome, Italy.

Gillham, F.E.M., Bell, T.M., Arin, T., Matthews, T.A., Rumeur, C.L., Hearn, A.B., 1995. Cotton production prospects for the next decade. World Bank Technical Paper Number, vol. 287. the World Bank, Washington, DC.

Glantz, M.H., 1998. Creeping environmental problems in the Aral Sea basin. In: Kobori, I., Glantz, M.H. (Eds.), Central Eurasian Water Crisis: Caspian, Aral and Dead Seas. United Nations University Press, New York.

Hall, M., Dixon, J., Gulliver, A., Gibbon, D. (Eds.), 2001. Farming Systems and Poverty: Improving Farmer's Livelihoods in a Changing World. FAO and World Bank, Rome.

Herendeen, R.A., 2004. Energy analysis and EMERGY analysis—A comparison. Ecol. Model. 178, 227–237.

Hoekstra, A.Y., 1998. Perspectives on Water: A Model-Based Exploration of the Future International Books. Utrecht, the Netherlands.

Hoekstra, A.Y., Hung, P.Q., 2002. Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series, vol. 11. UNESCO-IHE, Delft, the Netherlands.

Hoekstra, A.Y., Hung, P.Q., 2005. Globalisation of water resources: international virtual water flows in relation to crop trade. Glob. Environ. Change 15 (1), 45–56.

IFA, IFDC, IPI, PPI, FAO, 2002. Fertilizer Use By Crop. Food and Agriculture Organization, Rome, Italy.

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

Loh, J., Wackernagel, M., 2004. Living Planet Report. WWF, Gland, Switzerland.

Pereira, L.S., Cordery, I., Iacovides, I., 2002. Coping with water scarcity. International Hydrological Programme. UNESCO, Paris.

Postel, S., 1992. Last Oasis: Facing Water Scarcity. W.W. Norton and Company, New York.

Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable fresh water. Science 271, 785–788.

Proto, M., Supino, S., Malandrino, O., 2000. Cotton: a flow cycle to exploit. Ind. Crops Prod. 11 (2–3), 173–178.

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

Ren, X., 2000. Development of environmental performance indicators for textile process and product. J. Clean. Prod. 8 (6), 473–481.

Serageldin, I., 1995. Water resources management: a new policy for a sustainable future. Water Int. 20 (1), 15–21.

Seuring, S., 2004. Integrated chain management and supply chain management: comparative analysis and illustrative cases. J. Clean. Prod. 12, 1059–1071.

Shiklomanov, I.A., 2000. Appraisal and assessment of world water resources. Water. Int. 25 (1), 11–32.

Silvertooth, J.C, Navarro, J.C., Norton, E.R., Galadima, A., 2001. Soil and Plant Recovery of Labeled Fertilizer Nitrogen in Irrigated Cotton, Arizona Cotton Report. University of Arizona.

Soth, J., Grasser, C., Salerno, R., 1999. The Impact of Cotton on Fresh Water Resources and Ecosystems: A Preliminary Analysis. WWF, Gland, Switzerland.

UNCTAD, 2005a. Planting and Harvesting Times for Cotton, by Producing Country. http://r0.unctad.org/infocomm/anglais/cotton/crop.htm.

UNCTAD, 2005b. Cotton uses, http://r0.unctad.org/infocomm/anglais/cotton/uses.htm.

UNEP, 2002. Global environment outlook. Past, Present And Future Perspectives, vol. 3. Earthscan Publications, London.

UNEP IE, 1996. Cleaner Production in Textile Wet Processing: A Workbook for Trainers. United Nations Environment Programme: Industry and Environment, Paris.

USDA, 2004. Cotton: World markets and trade, http://www.fas.usda.gov/cotton/circular/2004/07/CottonWMT.pdf.

USDA/NOAA, 2005a. Major world crop areas and climatic profiles, USDA/NOAA Joint Agricultural Weather Facility, http://www.usda.gov/agency/oce/waob/mississippi/MajorWorldCropAreas.pdf.

USDA/NOAA, 2005b. Cotton—World supply and demand summary, USDA/NOAA Joint Agricultural Weather Facility, http://www.tradefutures.cc/education/cotton/worldsd.htm.

USEPA, 1996. Best Management Practices for Pollution Prevention in the Textile Industry. www.e-textile.org.

Van den Bergh, J.C.J.M., Verbruggen, H., 1999. Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint'. Ecol. Econ. 29, 61–72.

Van Kooten, G.C., Bulte, E.H., 2000. The ecological footprint: useful science or politics. Ecol. Econ. 32, 385–389.

Visvanathan, C., Kumar, S., Han, S., 2000. Cleaner production in textile sector: Asian scenario, Paper presented at the 'National Workshop on Sustainable Industrial Development through Cleaner Production', 12–13 November, Colombo, Sri Lanka.

Vörösmarty, C.J., Sahagian, D., 2000. Anthropogenic disturbance of the terrestrial water cycle. BioScience 50 (9), 753–765.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.

Wackernagel, M., Rees, W., 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers, Gabriola Island, B.C., Canada.

Wackernagel, M., Onisto, L., Linares, A.C., Falfan, I.S.L., Garcia, J.M., Guerrero, I.S., Guerrero, M.G.S., 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., Onisto, L., Bello, P., Linares, A.C., Falfan, I.S.L., Garcia, J.M., Guerrero, A.I.S., Guerrero, M.G.S., 1999. National natural capital accounting with the ecological footprint concept. Ecol. Econ. 29, 375–390.

WB, 1999. Pollution Prevention and Abatement Handbook 1998: Toward Cleaner Production. World Bank, Washington, DC.

WWF, 2003. Thirsty crops: our food and clothes: eating up nature and wearing out the environment? Living Waters: Conserving The Source of Life. WWF, The Netherlands.