UNESCO-IHE
Institute for Water Education

WATER FOOTPRINTS OF NATIONS

A.K. CHAPAGAIN
A.Y. HOEKSTRA

VOLUME 1: MAIN REPORT

NOVEMBER 2004

VALUE OF WATER

RESEARCH REPORT SERIES NO. 16

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Summary

The water footprint concept has been developed in order to have an indicator 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. Closely linked to the water footprint concept is the virtual water concept. Virtual water is defined as the volume of water required to produce a commodity or service. International trade of commodities implies flows of virtual water over large distances. The water footprint of a nation can be assessed by taking the use of domestic water resources, subtract the virtual water flow that leaves the country and add the virtual water flow that enters the country.

The *internal water footprint* of a nation is the volume of water used from domestic water resources to produce the goods and services consumed by the inhabitants of the country. The *external water footprint* of a country 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 aims to calculate the water footprint for each nation of the world for the period 1997-2001.

The use of domestic water resources comprises water use in the agricultural, industrial and domestic sectors. The total volume of water use in the agricultural sector is calculated based on the total volume of crop produced and its corresponding virtual water content. The virtual water content (m^3/ton) of primary crops is calculated based on crop water requirements and yields. The crop water requirement of each crop is calculated using the methodology developed by FAO. 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 is calculated based on the virtual water content of their feed and the volumes of drinking and service water consumed during their lifetime. The calculation of the virtual water content of livestock products is again based on product fractions and value fractions. Virtual water flows between nations are derived from statistics on international product trade and the virtual water content per product in the exporting country.

The global volume of water used for crop production, including both effective rainfall and irrigation water, is 6390 Gm^3/yr. In general, crop products have lower virtual water content than livestock products. 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 global volume of virtual water flows related to the international trade in commodities is 1625 Gm^3/yr. About 80% of these virtual water flows relate to the trade in agricultural products, while the remainder is related to industrial product trade.

The global water footprint is 7450 Gm^3/yr, which is 1240 m^3/cap/yr. The differences between countries are large: the USA has an average water footprint of 2480 m^3/cap/yr, while China has an average footprint of 700 m^3/cap/yr. The four major 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).

The countries with a relatively high rate of evapotranspiration and a high gross national income per capita (which often results in large consumption of meat and industrial goods) have large water footprints, such as: Portugal (2260 m^3/yr/cap), Italy (2330 m^3/yr/cap) and Greece (2390 m^3/yr/cap). Some countries with a high gross national income per capita can have a relatively low water footprint due to favourable climatic conditions for crop production, such as the United Kingdom (1245 m^3/yr/cap), the Netherlands (1220 m^3/yr/cap), Denmark (1440 m^3/yr/cap) and Australia (1390 m^3/yr/cap). Some countries can exhibit a high water footprint because of high meat proportions in the diet of the people and high consumption of industrial products, such as the USA (2480 m^3/yr/cap) and Canada (2050 m^3/yr/cap).

International water dependency is substantial. An estimated 16% of the global water use is not for producing domestically consumed products but products for export. With increasing globalisation of trade, global water interdependencies are likely to increase.

1. Introduction

1.1. The water footprint concept: an indicator of water use in relation to consumption

People use lots of water for drinking, cooking and washing, but even more for producing things such as food, paper, cotton clothes, etc. The water footprint of an individual, business or nation is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual, business or 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. In order to give a complete picture of water use, the water footprint includes both the water withdrawn from surface and groundwater and the use of soil water (in agricultural production).

The water footprint concept was introduced by Hoekstra in 2002 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. Databases on water use traditionally show three columns of water use: water withdrawals in the domestic, agricultural and industrial sector respectively. 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 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.

The water footprint has been developed in analogy to the ecological footprint concept as was introduced in the second half of the 1990s (Wackernagel and Rees, 1996; Wackernagel *et al*, 1997; Wackernagel and Jonathan, 2001). 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 shows the *area* needed to sustain people’s living, the ‘water footprint’ indicates the *annual water volume* required to sustain a population.

The first assessment of water footprints of nations was carried out by Hoekstra and Hung (2002). A more extended assessment was done by Chapagain and Hoekstra (2003a). We can now easily say that the previous studies should be considered as rudimentary. The current study attempts to improve the assessment through using more accurate basic data, covering more products than before and by refining the methodology where it appeared necessary.

1.2. Virtual water flows between nations: countries making use of water resources elsewhere in the world

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 flow that leaves the country and add the virtual water flow that enters the country.

In the past few years a number of studies have become available that show that the virtual water flows between nations are substantial. All studies showed that the global sum of international virtual water flows must exceed 1000 billion cubic metres per year (Hoekstra and Hung, 2002; Chapagain and Hoekstra, 2003a; Zimmer and Renault, 2003; Oki *et al*., 2003).

Knowing the virtual water flows entering and leaving a country can put a completely new light on the actual water scarcity of a country. Jordan, as an example, imports about 5 to 7 billion cubic metre of virtual water per year (Chapagain and Hoekstra, 2003a; Haddadin, 2003), which is in sheer contrast with the 1 billion cubic metre of annual water withdrawal from domestic water sources. As another example, Egypt, with water self-sufficiency high on the political agenda and with a total water withdrawal inside the country of 65 billion cubic metre per year, still has an estimated net virtual water import of 10 to 20 billion cubic metre per year (Yang and Zehnder, 2002; Chapagain and Hoekstra, 2003a; Zimmer and Renault, 2003).

In an open world economy, according to international trade theory, the people of a nation will seek profit by trading products that are produced with resources that are abundantly available within the country for products that need resources that are scarcely available. People in countries where water is a comparatively scarce resource, could thus aim at importing products that require a lot of water in their production (water-intensive products) and exporting products or services that require less water (water-extensive products). This *import of virtual water* (as opposed to import of real water, which is generally too expensive) will relieve the pressure on the nation's own water resources. For water-abundant countries an argumentation can be made for *export of virtual water*.

1.3. Objective of the study

The objective of this study is to assess and analyse the water footprints of nations. Given the available data, it has been chosen to use the years 1997-2001 as the period of analysis. National water footprints can be assessed in two ways. The bottom-up approach is to consider the sum of all goods and services consumed multiplied with their respective virtual water content, where the virtual water content of a good will vary as a function of place and conditions of production. In the top-down approach, the water footprint of a nation is calculated as the total use of domestic water resources plus the virtual water flows entering the country minus the virtual water flows leaving the country. This study aims to apply the top-down approach. Subsequent study will be aimed to adopt the bottom-up approach.

This study builds on two earlier studies. Hoekstra and Hung (2002) have quantified the virtual water flows related to the international trade of crop products. Chapagain and Hoekstra (2003a) have done a similar study for livestock and livestock products. The concerned time period in these two studies is 1995-99. The present study takes the period of 1997-2001 and refines the earlier studies by making improvements and extensions as explained in Appendix XXII.

2. Method

2.1. Calculation of the water footprint of a nation

The water footprint of a country (WFP, m^3/yr) is equal to the total volume of water used, directly or indirectly, to produce the goods and services consumed by the inhabitants of the country. A national water footprint has two components, the internal and the external water footprint:

$$WFP = IWFP + EWFP \tag{1}$$

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 (VWE_{dom}, m^3/yr).

$$IWFP = AWU + IWW + DWW - VWE_{dom} \tag{2}$$

The first three components represent the total water volume used in the national economy (in m^3/yr): AWU is the agricultural water use, taken equal to the evaporative water demand of the crops, and IWW and DWW are the water withdrawals in the industrial and domestic sectors respectively. The agricultural water use includes both effective rainfall (the portion of the total precipitation which is retained by the soil so that it is available for use for crop production (FAO, 2004) 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* ($EWFP$) of a country 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 (VWI, m^3/yr) *minus* the volume of virtual water exported to other countries as a result of re-export of imported products ($VWE_{re\text{-}export}$).

$$EWFP = VWI - VWE_{re-export} \tag{3}$$

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).

In order to make cross-country comparisons, it is useful to calculate the average water footprint per capita per country (WFP_{pc}, $m^3/cap/yr$):

$$WFP_{pc} = \frac{WFP}{Total \quad population} \tag{4}$$

The steps in the water footprint calculation are schematically shown in Figure 2.1. A detailed description of the calculation steps involved is given the next sections.

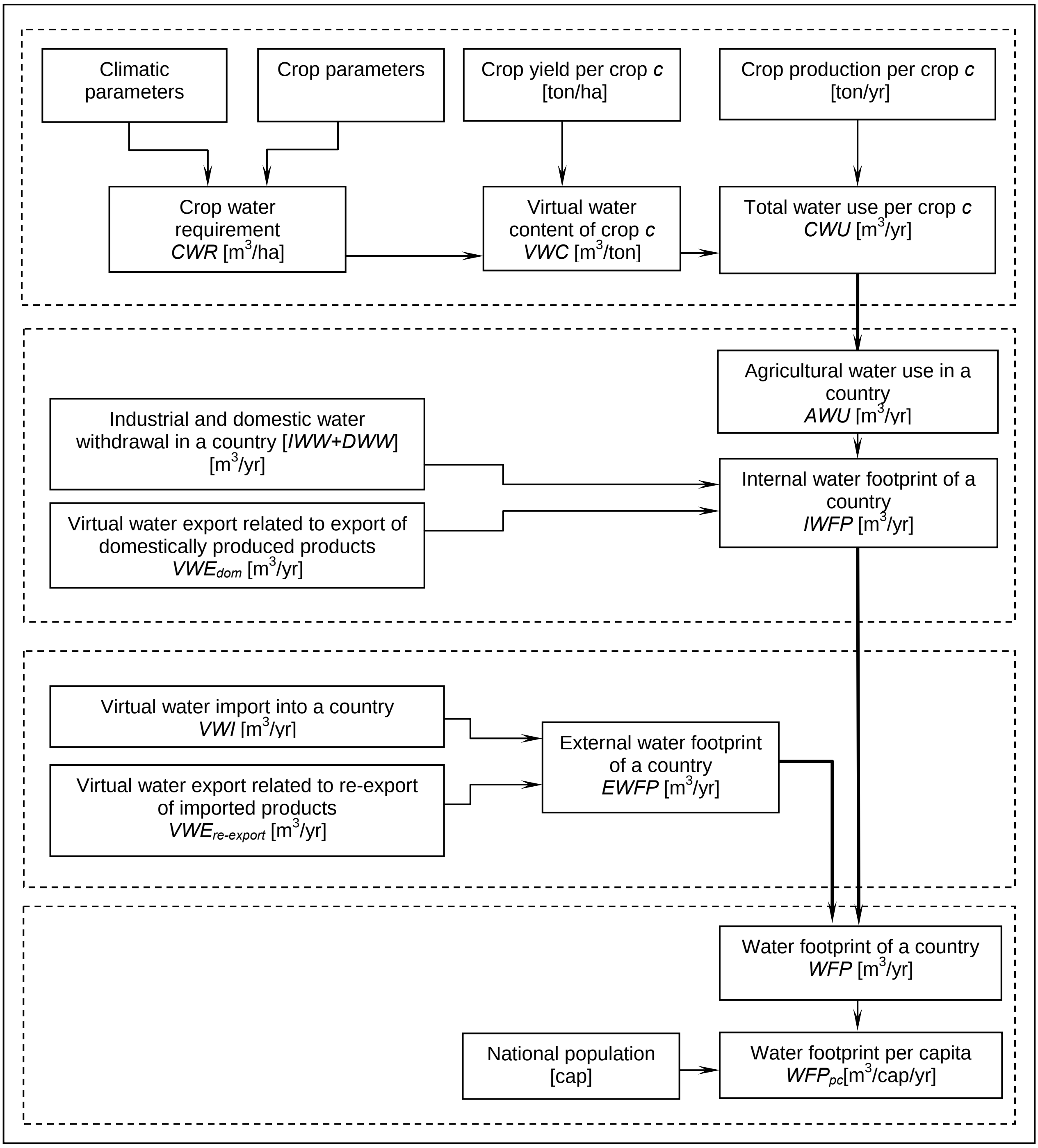


Figure 2.1. Steps in the calculation of the water footprint of a nation. The steps in the calculation of virtual water export from or import into a country are shown in Figure 2.5.

2.2. Use of domestic water resources

2.2.1. Water use for crop production

The total volume of water use to produce crops in a country (*AWU*, m^3/yr), is calculated as:

$$AWU = \sum_{c=1}^{n_c} CWU[c] \qquad (5)$$

where *CWU* (m^3/yr), crop water use, is the total volume of water used in order to produce a particular crop.

$$CWU[c] = CWR[c] \times \frac{Production[c]}{Yield[c]} \qquad (6)$$

Here, *CWR* is the crop water requirement measured at field level (m^3/ha), *Production* the total volume of crop *c* produced (ton/yr) and *Yield* the production volume of crop *c* per unit area of production (ton/ha).

'Crop water requirement' is defined as the total water needed for evapotranspiration, from planting to harvest for a given crop in a specific climate regime, when adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield (Allen *et al.*, 1998). Under standard conditions when a crop grows without any shortage of water, the crop evapotranspiration is equal to the *CWR* of a crop. By taking crop water requirements as an indicator of actual crop water use, we implicitly assume that the crop water requirements are fully met. This leads to an overestimation of actual crop water use. On the other hand, however, we underestimate the water needs to grow crops by excluding irrigation losses and drainage requirements from our analysis. In order to reduce the error made when taking crop water use a function of crop water requirement, countries where crop yields are very low due to water constraints have been left out from the analysis.

The crop water requirement is calculated by accumulation of data on daily crop evapotranspiration ET_c (mm/day) over the complete growing period.

$$CWR[c] = 10 \times \sum_{d=1}^{lp} ET_c[c,d] \qquad (7)$$

Where the factor 10 is meant to convert mm into m^3/ha and where the summation is done over the period from day 1 to the final day at the end of the growing period (*lp* stands for length of growing period in days). The crop water requirement of rice cannot be calculated directly using Equation 7. In addition to evapotranspiration from the paddy field, there is a considerable amount of percolation from the field, which varies with the soil type and ground water table at the farm. Assuming that rice is normally grown in a loam and loamy clay, we have added 300 mm of water for percolation during plantation period.

The crop evapotranspiration per day follows from multiplying the reference crop evapotranspiration ET_0 with the crop coefficient K_c:

$$ET_c[c] = K_c[c] \times ET_0 \tag{8}$$

The reference crop evapotranspiration is the evapotranspiration rate from a reference surface, not short of water. The reference is a hypothetical surface with extensive green grass cover with specific characteristics. The only factors affecting ET_o are climatic parameters. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. The actual crop evapotranspiration differs distinctly from the reference evapotranspiration, as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (K_c).

The major factors determining K_c are crop variety, climate and crop growth stage. For instance, more arid climates and conditions of greater wind speed will have higher values for K_c. More humid climates and conditions of lower wind speed will have lower values for K_c.

As the crop develops, the ground cover, crop height and the leaf area change. Due to differences in evapotranspiration during the various growth stages, the K_c for a given crop will vary over the growing period. The growing period can be divided into four distinct growth stages: initial, crop development, mid-season and late season (Figure 2.2).

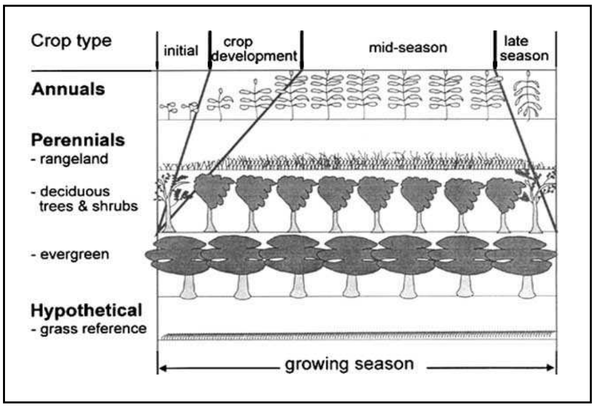


Figure 2.2. Crop growth stages for different types of crops (Allen et al., 1998).

The *initial stage* runs from planting date to approximately 10% ground cover. The length of the initial period is highly dependent on the crop, the crop variety, the planting date and the climate. For perennial crops, the planting date is replaced by the 'green up' date, i.e., the time when the initiation of new leaves occurs. During the initial period, the leaf area is small, and evapotranspiration is predominately in the form of soil evaporation. Therefore, the K_c during the initial period is large when the soil is wet from irrigation and rainfall and is low when the soil surface is dry.

The *crop development stage* runs from 10% ground cover to effective full cover, which for many crops occurs at the initiation of flowering. As the crop develops and shades more and more of the ground, evaporation becomes more restricted and transpiration gradually becomes the major process. During the crop development stage, the K_c value corresponds to the extent of ground cover. Typically, if the soil surface is dry, $K_c = 0.5$ corresponds to about 25-40% of the ground surface covered by vegetation. A K_c value of 0.7 often corresponds to about 40-60% ground cover. These values will vary, depending on the crop, frequency of wetting and whether the crop uses more water than the reference crop at full ground cover.

The *mid-season stage* runs from effective full cover to the start of maturity. The start of maturity is often indicated by the beginning of the ageing, yellowing or senescence of leaves, leaf drop, or the browning of fruit to the degree that the crop evapotranspiration is reduced relative to the reference ET_o. The mid-season stage is the longest stage for perennials and for many annuals, but it may be relatively short for vegetable crops that are harvested fresh for their green vegetation. In the mid-season stage K_c has its maximum value and remains constant. Deviation of K_c from the reference value '1' is primarily due to differences in crop height and resistance between the grass reference surface and the actual crop surface.

The *late season* stage runs from the start of maturity to harvest or full senescence. The calculation of crop evapotranspiration is presumed to end when the crop is harvested, dries out naturally, reaches full senescence, or experiences leaf drop. For some perennial vegetation in frost-free climates, crops may grow year round so that the date of termination may be taken the same as the date of 'planting'. The K_c value at the end of the late season stage reflects crop and water management practices. The K_c value is high if the crop is frequently irrigated until harvested fresh. If the crop is allowed to senesce and to dry out in the field before harvest, the K_c value will be small.

The K_c curve looks like as shown in Figure 2.3. As an example, the K_c curve for wheat grown in India is shown in Figure 2.4.

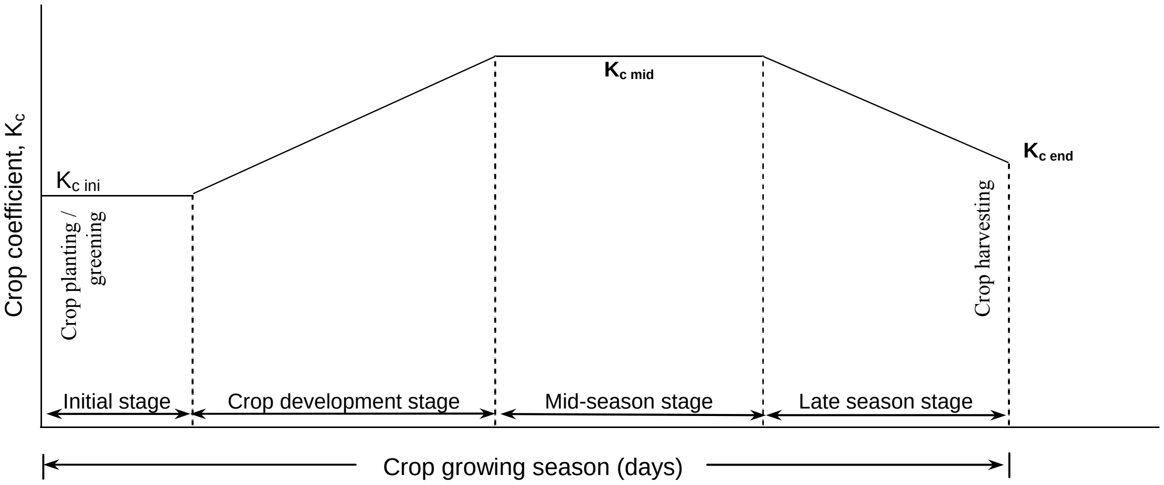


Figure 2.3. Development of K_c during the crop growing season.

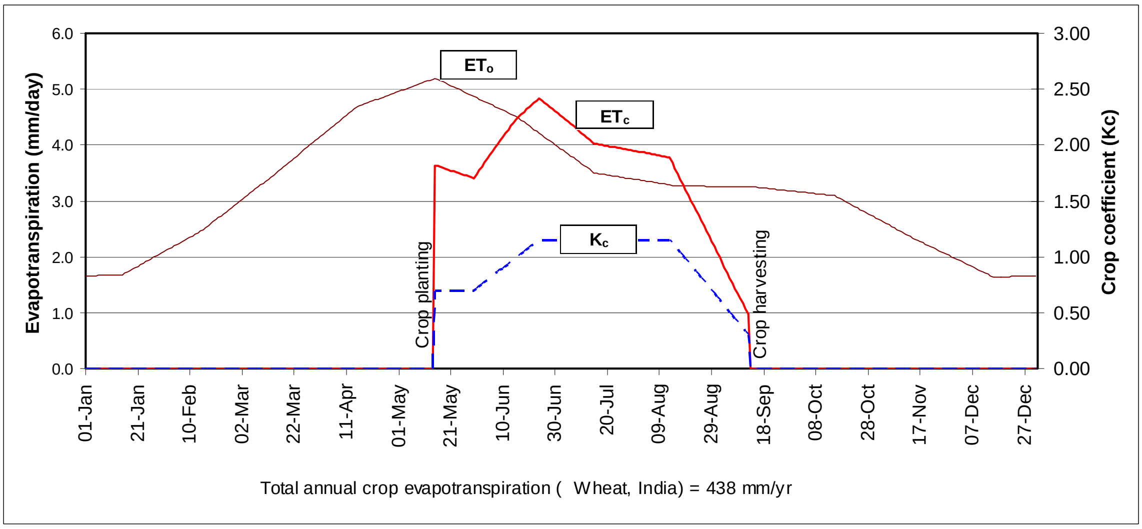


Figure 2.4. Calculation of ET_c for wheat grown in India. It also shows the daily distribution of ET_0 (mm/day) for India and K_c for wheat planted on 15th of December in India.

Reference crop evapotranspiration

The FAO Penman-Monteith method is used to estimate the reference evapotranspiration ET_0. Below we summarize the method from FAO (Allen *et al.*, 1998),

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{9}$$

Where

ET_0 = reference crop evapotranspiration [mm/day],
Δ = slope of the vapour pressure curve [kPa/°C] (Equation 10),
T = average air temperature [°C] (Equation 11),
γ = psychrometric constant [kPa/°C] (Equation 12),
e_s = saturation vapour pressure [kPa] (Equation 14),
R_n = net radiation at the crop surface [MJ/m^2/day] (Equation 16),
G = soil heat flux [MJ/m^2/day] (Equation 26),
U_2 = wind speed measured at 2 m height [m/s],
e_a = actual vapour pressure [kPa],
e_s-e_a = vapour pressure deficit [kPa].

Equation 9 is applied with a time step of a month. For all input data, monthly averages have been taken. A smooth graph of ET_0 over the year has been obtained by assuming that the calculated monthly averages hold for the 15th of the month and by assuming linear development in between the 15th of one month and 15th of next month. The various parameters in Equation 9 are calculated in different steps.

Slope of saturation vapour pressure curve (Δ)

$$\Delta = \frac{4098 \times \left[0.6108 \times \exp\left(\frac{17.27 \times T}{(T + 237.3)}\right)\right]}{(T + 237.3)^2} \qquad (10)$$

Where

Δ = slope of saturation vapour pressure curve at air temperature T [kPa/°C],

T = air temperature [°C] (Equation 11),

exp(..) = 2.7183 (base of natural logarithm) raised to the power (..).

The slope of the vapour pressure curve is calculated using mean air temperature T_{mean}.

$$T_{mean} = \frac{T_{\max} + T_{\min}}{2} \qquad (11)$$

Where

T_{max} = daily maximum temperature,

T_{min} = daily minimum temperature.

Psychrometric constant (γ)

$$\gamma = \frac{c_p \times P}{\varepsilon \times \lambda} = 0.665 \times 10^{-3} \times P \qquad (12)$$

Where

γ = psychrometric constant [kPa/°C],

P = atmospheric pressure [kPa] (Equation 13),

λ = latent heat of vaporization, 2.45 [MJ/kg],

c_p = specific heat at constant pressure, 1.013×10^{-3} [MJ/kg/°C],

ε = ratio molecular weight of water vapour/dry air = 0.622.

The specific heat at constant pressure is the amount of energy required to increase the temperature of a unit mass of air by one degree at constant pressure. For average atmospheric conditions a value $c_p = 1.013 \times 10^{-3}$ MJ/kg/°C can be used. Atmospheric pressure P in kPa for a location (at an elevation of z m above mean sea level) is calculated as follows:

$$P = 101.3 \times \left(\frac{293 - 0.0065 \times z}{293}\right)^{5.26} \qquad (13)$$

Mean saturation vapour pressure (e_s)

$$e_s = \frac{e^0{}_{(T\max)} + e^0{}_{(T\min)}}{2} \tag{14}$$

Where $e^0{}_{(Tmax)}$ and $e^0{}_{(Tmin)}$ are calculated as follows:

$$e^0{}_{(T)} = 0.6108 \times \exp\left(\frac{17.27 \times T}{(T + 237.3)}\right) \tag{15}$$

Net radiation (R_n)

The net radiation is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl} \tag{16}$$

The net shortwave radiation ($R_{ns,}$) resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = (1 - \alpha) \times R_s \tag{17}$$

Where

R_{ns} = net solar or shortwave radiation [MJ/m^2/day],

α = albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop,

R_s = the incoming solar radiation [MJ/m^2/day] (Equation 19).

Net longwave radiation (R_{nl}) is given by the Stefan-Boltzmann equation.

$$R_{nl} = \sigma \times \left[\frac{T^4{}_{(\max,K)} + T^4{}_{(\min,K)}}{2}\right] \times \left(0.34 - 0.14\sqrt{e_a}\right) \times \left(1.35 \times \frac{R_s}{R_{s0}} - 0.35\right) \tag{18}$$

Where

R_{nl} = net outgoing longwave radiation [MJ/m^2/day],

σ = Stefan-Boltzmann constant [4.903 x 10^{-9} MJ/K^4/m^2/day],

$T_{max,\,K}$ = maximum absolute temperature during the 24-hour period [K = °C + 273.16],

$T_{min,\,K}$ = minimum absolute temperature during the 24-hour period [K = °C + 273.16],

e_a = actual vapour pressure [kPa],

R_s/R_{so} = relative shortwave radiation (limited to ≤ 1.0),

R_s = solar radiation [MJ/m^2/day] (Equation 19),

R_{so} = clear-sky radiation [MJ/m^2/day] (Equation 20).

Solar radiation (R_s) can be calculated with the Angstrom formula, which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left(a_s + b_s \times \frac{n}{N} \right) \times R_a \tag{19}$$

Where

R_s = solar or shortwave radiation [MJ/m^2/day],

n = actual duration of sunshine [hour],

N = maximum possible duration of sunshine or daylight hours [hour],

n/N = relative sunshine duration = (1-Percentage cloud cover expressed in fraction) [dimensionless],

R_a = extraterrestrial radiation [MJ/m^2/day] (Equation 21),

a_s = regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0),

a_s+b_s = fraction of extraterrestrial radiation reaching the earth on clear days (when n = N).

Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month), the Angstrom values a_s and b_s will vary. Where no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values $a_s = 0.25$ and $b_s = 0.50$ are taken as recommended by Allen *et al*. (1998).

The clear-sky radiation, R_{so}, when n = N, is calculated as:

$$R_{s0} = \left(0.75 + 2 \times 10^{-6} \times z\right) \times R_a \tag{20}$$

Where, R_a is extraterrestrial radiation (MJ/m^2/day, Equation 21) and z is the elevation above mean sea level (m). The extraterrestrial radiation, R_a, for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year.

$$R_a = \frac{24 \times (60)}{\pi} G_{sc} \times d_r \left[\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s) \right] \tag{21}$$

Where

R_a = extraterrestrial radiation [MJ/m^2/day],

G_{sc} = solar constant = 0.0820 [MJ/m^2/day],

d_r = inverse relative distance Earth-Sun (Equation 22),

ω_s = sunset hour angle [rad] (Equation 25),

φ = latitude [rad] (Equation 24),

δ = solar decimation [rad] (Equation 23).

The inverse relative distance Earth-Sun, d_r, and the solar declination, δ, are given by:

$$d_r = 1 + 0.033 \times \cos\left(\frac{2\pi}{365} J\right) \tag{22}$$

$$\delta = 0.409 \times \sin\left(\frac{2\pi}{365} J - 1.39\right) \tag{23}$$

Where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). The latitude, φ, expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere.

$$\varphi[\text{radians}] = \frac{\pi}{180}[\text{decimal degrees}] \tag{24}$$

The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \tag{25}$$

Soil heat flux (G)

Complex models are available to describe soil heat flux. Because soil heat flux is small compared to R_n, particularly when the surface is covered by vegetation, for monthly average G, we can use the following:

$$G_{month,i} = 0.07 \times \left(T_{month,i+1} - T_{month,\ i-1}\right) \tag{26}$$

Where

$T_{month,\ i}$ = mean air temperature of month i [°C] (Equation 11),
$T_{month,\ i-1}$ = mean air temperature of previous month [°C] (Equation 11),
$T_{month,\ i+1}$ = mean air temperature of next month [°C] (Equation 11).

2.2.2. Water use in the industrial and domestic sectors

For data on water use in the industrial and domestic sectors we use available statistics. The industrial water withdrawal includes process water required in different stages of production. Domestic water withdrawal incorporates the blue water withdrawn to meet the per capita demand for household and municipal consumption.

2.3. The export of domestic water resources and the import of foreign water resources

2.3.1. Virtual water content of primary crops

The virtual water content of a crop c in a country (m^3/ton) is calculated as the ratio of total water used for the production of crop c to the total volume of crop produced in that country.

$$VWC\ [c] = \frac{CWU\ [c]}{Production\ \ [c]} \tag{27}$$

where $CWU\ [c]$ is the volume of water use at farm level for the production of crop c in the country (m^3/yr) and $Production\ [c]$ the total volume of crop c produced per year in the country (ton/yr).

2.3.2. Virtual water content of live animals

The virtual water content of an animal at the end of its life span is defined as the total volume of water that was used to grow and process its feed, to provide its drinking water, and to clean its housing and the like. It depends on the breed of an animal, the farming system, the feed consumption and the climatic conditions of the place where the feed is grown.

There are three components to the virtual water content (VWC) of a live animal a:

$$VWC\ [a] = VWC_{feed}[a] + VWC_{drink}[a] + VWC_{serv}[a] \tag{28}$$

VWC_{feed}[a], $VWC_{drink}[a]$ and $VWC_{serv}[a]$ represent the virtual water content of animal a related to feed, drinking water and service water consumption respectively, expressed in cubic metres of water per ton of live animal.

The virtual water content of an animal at the end of its life span from the feed consumed has two parts. The first is the actual water that is required to prepare the feed mix and the second is the virtual water incorporated in the various feed ingredients.

$$VWC_{feed}[a] = \frac{\int_{birth}^{slaughter} \left\{ q_{mixing}[a] + \sum_{c=1}^{n_c} VWC[c] \times Feed[a,c] \right\} dt}{W[a]} \tag{29}$$

The variable $q_{mixing}\ [a]$ represents the volume of water required for mixing the feed (m^3/day). $Feed[a,c]$ is the quantity of feed crop c consumed by the animal, expressed in tons per day. $W\ [a]$ is the live weight of the animal at the end of its life span, expressed in tons.

The virtual water content of an animal originating from drinking is equal to the total volume of water withdrawn for drinking water supply, calculated over the entire life span of the animal.

$$VWC_{drink}[a] = \frac{\int_{birth}^{slaughter} q_d[a]dt}{W[a]} \tag{30}$$

The virtual water content of an animal from the service water used is equal to the total volume of water used to clean the farmyard, wash the animal and other services necessary to maintain the environment during the entire life span of the animal.

$$VWC_{serv}[a] = \frac{\int_{birth}^{slaughter} q_{serv}[a]dt}{W[a]} \tag{31}$$

$q_d[a]$ and $q_{serv}[a]$ are the daily drinking water requirement and the daily service water requirement of the animal respectively (m^3/day).

2.3.3. Virtual water content of processed crop and livestock products

The virtual water content of a processed product depends on the virtual water content of the primary crop or live animal from which it is derived. The virtual water content of the primary crop or live animal is distributed over the different products from that specific crop or animal. We have assumed that each individual crop or livestock product p comes from one and only one particular type of primary crop c or live animal a. For simplification it is further assumed that a product p exported from a certain country e is actually produced from a primary crop c or animal a grown within that country using the domestic resources only.

For the sake of systematic analysis we assume ‘levels of production’. The products derived directly from a primary crop or a live animal are called primary products. For example, cows produce milk, a carcass and skin as their primary products. From paddy (rice) we get husked rice as a primary crop product. From soybean we get soybean crude oil and soybean oil cakes as primary crop products. Some of these primary products are further processed into so-called secondary products, such as cheese and butter made from the primary product milk, flour made from husked rice and meat and sausage processed from the carcass.

The virtual water content of a processed product from a primary crop or a live animal includes (part of) the virtual water content of the primary crop or live animal plus the processing water needed. The processing water requirement is calculated as follows:

$$PWR\,[c\,or\,a] = \frac{Q_{proc}\,[c\,or\,a]}{W\,[c\,or\,a]} \tag{32}$$

Here $PWR[c$ or $a]$ is the processing water requirement per ton of primary crop c or live animal a for producing primary products in a country (m^3/ton). $Q_{proc}[c$ or $a]$ is the total volume of processing water required (m^3) to process crop c or animal a. $W[c$ or $a]$ is the total weight of the primary crop or live animal processed.

The sum of processing water requirement (*PWR*) and the virtual water content of the primary crop (VWC_c) or the virtual water content of the live animal (VWC_a) should be attributed to the processed products in a logical way. To do this we introduce the terms *product fraction* and *value fraction*. The product fraction $pf[p]$ of product p is defined as the weight of the primary product obtained per ton of primary crop or live animal (Chapagain and Hoekstra, 2003a). For example, if one ton of paddy (rice) produces 0.62 ton of husked rice, the product fraction of husked rice is 0.62. The *pf*'s for crop and livestock products are calculated respectively as follows:

$$pf[p] = \frac{W_p[p]}{W[c]} \tag{33a}$$

$$pf[p] = \frac{W_p[p]}{W[a]} \tag{33b}$$

Here $W_p[p]$ is the weight of primary product p obtained from processing $W[c]$ ton of primary crop c or $W[a]$ ton of live animal a. Generally the product fraction is less than one, because the product is derived from just part of the animal or crop. However, if a product is obtained during the lifetime of an animal, as in the case of milk and eggs, the *pf* can be greater than one (Chapagain and Hoekstra, 2003a).

If there are more than two products obtained while processing a primary crop or a live animal, we need to distribute the virtual water content of the primary crop or the live animal to its products based on value fractions and product fractions. The value fraction, $vf[p]$, of a product is the ratio of the market value of the product to the aggregated market value of all the products obtained from the primary crop or live animal:

$$vf[p] = \frac{v[p] \times pf[p]}{\sum (v[p] \times pf[p])} \tag{34}$$

The denominator is totalled over the primary products that originate from the primary crop c or the animal a. The variable $v[p]$ is the market value of product p (US\$/ton). Hence, the virtual water content (*VWC*) of primary product p in m^3/ton is:

$$VWC[p] = \left(VWC[c \,\mathrm{or}\, a] + PWR[c \,\mathrm{or}\, a]\right) \times \frac{vf[p]}{pf[p]} \tag{35}$$

In a similar way we can calculate the virtual water content for secondary and tertiary products, etc. The first step is always to obtain the virtual water content of the input (root) product and the water necessary to process it. The total of these two elements is then distributed over the various output products, based on their product fraction and value fraction. The list of crop products and their product fractions is presented in Appendix X.

For example, 1 ton of soybean produces 0.85 tons of soybean flour. If the virtual water content of soybean is 1789 m^3/ton, the virtual water content of soybean flour is 2105 (= 1789/0.85) m^3/ton. Instead of processing soybeans into soybean flour, we can also process soybeans into soybean crude oil ($pf_{soybean\ crude\ oil} = 0.18$ ton per ton of soybean) and soybean oil cake ($pf_{soybean\ oil\ cake} = 0.79$ ton per ton of soybean). The global average market value of soybean crude oil is 502 US$/ton and soybean oil cake is 219 US$/ton. The total market value of soybean crude oil is, thus, 90 US$ (= 502*0.18) and the market value of soybean oil cake produced is 173 US$ (=0.79*219). The total market value produced is 263 US$ (= 90+173). Hence, the value fraction of soybean crude oil is 0.343 ($vf_{soybean\ crude\ oil} = 90/263$) and for the soybean oil cake it is 0.657 ($vf_{soybean\ oil\ cake} = 173/263$). Neglecting process water requirements, the virtual water content of the two products from soybean can be calculated as:

$$\text{Virtual water content of soybean crude oil} = \frac{VWC_{soybean} * vf_{soybean\ crude\ oil}}{pf_{soybean\ crude\ oil}}$$

$$= \frac{1789 * 0.343}{0.18} \approx 3410\ \mathrm{m^3/ton}$$

$$\text{Virtual water content of soybean oil cake} = \frac{VWC_{soybean} * vf_{soybean\ oi\ cake}}{pf_{soybean\ oil\ cake}}$$

$$= \frac{1789 * 0.657}{0.79} \approx 1490\ \mathrm{m^3/ton}$$

2.3.4. Virtual water flows related to the trade in agricultural products

International virtual water flows related to trade in agricultural products are calculated by multiplying the trade volumes with their respective virtual water content. The virtual water content of a traded crop or livestock product depends on where and how the product has been produced. We assume here that the products have been produced in the exporting country.

The virtual water flow *VWF* (m^3/yr) from exporting country *e* to importing country *i* as a result of export of an agricultural product *p* can be calculated as:

$$VWF[e,i,p] = PT[e,i,p] \times VWC[e,p] \tag{36}$$

Here, *PT* represents the product trade (ton/yr) from exporting country *e* to importing country *i* while *VWC* is the virtual water content (m^3/ton) of product *p* in the exporting country.

2.3.5. Virtual water flows related to the trade in industrial 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 withdrawn in the industrial sector is only 716 Gm^3/yr (≈ 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 (*VWC*, m^3/US\$) as:

$$VWC[e] = \frac{IWW[e]}{GDP_i[e]} \tag{37}$$

Here *IWW* is the industrial water withdrawal (m^3/yr) in a country, while GDP_i is the added value of the industrial sector, which is one component of the national *GDP* (US\$/yr).

The global average virtual water content of industrial products (VWC_g) is defined as:

$$VWC_g = \frac{\sum_{e=1}^{n} IWW[e]}{\sum_{e=1}^{n} GDP_i[e]} \tag{38}$$

The total volume of virtual water exported from country *e* as a result of export of industrial products (*VWE*) is obtained by multiplying the export value of industrial products by the virtual water content per dollar (*VWC*).

$$VWE[e] = VWC[e] \times Export\ value\ of\ industrial\ products\,[e] \tag{39}$$

The virtual water import related to the import of industrial products (*VWI*) is calculated using the global average virtual water content in the industrial sector (VWC_g).

$$VWI[e] = VWC_g \times Import\ value\ of\ industrial\ products\,[e] \tag{40}$$

2.3.6. Virtual water balance of a country

The difference between total virtual water import and total virtual water export is the virtual water flow balance of the country in the time period concerned. If the balance is positive it implies net virtual water being imported and if it is negative there is net export of virtual water.

The various steps in the calculation of virtual water flows leaving and entering a country are presented schematically in Figure 2.5.

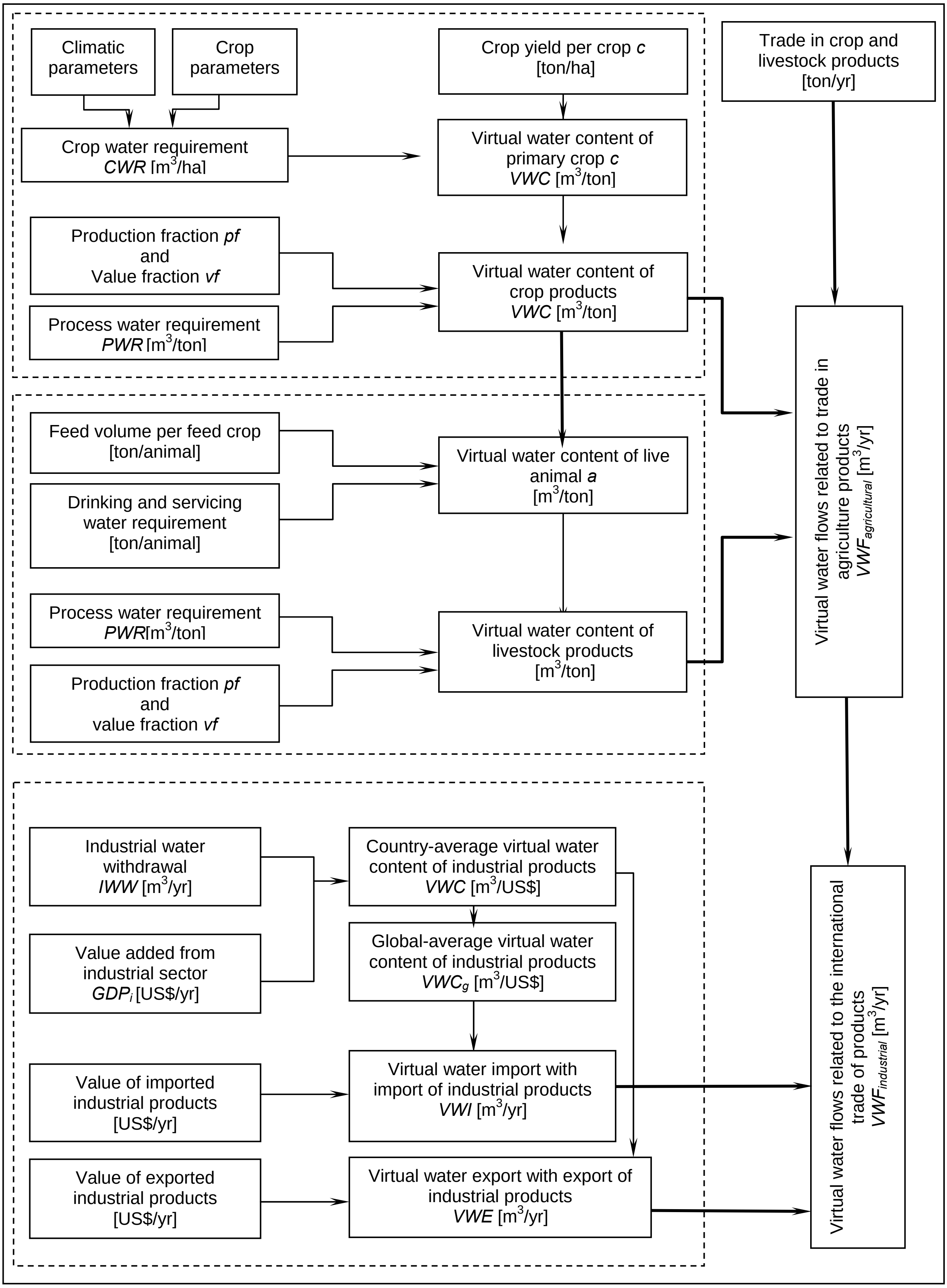


Figure 2.5. Steps in the calculation of virtual water flows of a country related to international trade of agricultural and industrial products.

2.4. Water scarcity, water self-sufficiency and water import dependency of a nation

We define *water scarcity* (*WS*) of a nation as the ratio of the nation's water footprint (*WFP*) to the nation's water availability (*WA*).

$$WS = \frac{WFP}{WA} \times 100 \tag{41}$$

The national water scarcity can be more than 100% if there is more water needed for producing the foods and services consumed by the people of a nation than is available in the country. As a measure of water availability we take here the 'total renewable water resources (actual)' as defined by FAO in their AQUASTAT database.

We define *water import dependency* (*WD,* %) of a nation as the ratio of the external water footprint (*EWFP*, m^3/yr) to the total water footprint (*WFP*, m^3/yr) of a country.

$$WD = \frac{EWFP}{WFP} \times 100 \tag{42}$$

National *water self-sufficiency* (*WSS,* %) is defined as the internal water footprint (*IWFP*, m^3/yr) divided by the total water footprint.

$$WSS = \frac{IWFP}{WFP} \times 100 \tag{43}$$

Self-sufficiency is 100% if all the water needed is available and indeed taken from within the own territory. Water self-sufficiency approaches zero if the demands of goods and services in a country are heavily met with gross virtual water imports, i.e. it has relatively large *external water footprint* in comparison to its *internal water footprint.*

3. Scope and data

3.1. Country coverage

For the calculation of reference evapotranspiration, crop water requirement and consequently virtual water content of different primary crops we have taken 210 countries (see Appendix II) for which the production and yield data are available in the on-line database of FAO (FAOSTAT, 2004).

For the calculation of international virtual water flows, that determine the external water footprints, we have taken into account the trade between 243 countries and territories for which international trade data are available in the Personal Computer Trade Analysis System (PC-TAS, 2004) of the International Trade Centre, UNCTAD/WTO. It covers trade data from 146 reporting countries and territories disaggregated by product and partner countries (UNSD, 2004a). The list of reporting and partner countries and territories as available in PC-TAS (2004) is presented in Appendix II.

For the 97 countries and territories that are not reporting country but are included as partner country nevertheless, the export and import data are estimated using mirror statistic from the trade data of the reporting countries. For example, if we want to estimate Viet Nam's exports to Indonesia, we look at what Indonesia reports about its imports from Viet Nam. This role reversal is used in cases where the concerned country has not been providing up-to-date information on its trade flow. It can also help as a means to double-check the reporter's information. The international trade flows between non-reporting countries are not covered in this study.

3.2. Product coverage

The total water footprint is calculated as the sum of the use of domestic water resources and virtual water import minus virtual water export. The use of domestic water resources is the sum of three components: volume of industrial water withdrawal, volume of domestic water withdrawal and crop evapotranspiration. Data on domestic water withdrawals have been taken from AQUASTAT (FAO, 2003f, g). We have assumed that the domestic water withdrawal is equal to the consumption. The study covers all the industrial products through a relatively simple approach. Per country, we simply consider total industrial water withdrawal as reported in AQUASTAT (FAO, 2003f, g). The volume of water used for crop production (crop evapotranspiration) in a country is estimated using the production data per country covering 164 types of primary crops (as defined in FAOSTAT, 2004). The list of primary crops and their product codes in FAOSTAT is presented in Appendix III.

The volume of virtual water export or import is calculated based on the international trade of products and their virtual water content. As for trade in agricultural products, we have taken trade data from PC-TAS (2004). The 28 relevant product groups in PC-TAS are presented in Table 3.1. 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.

Table 3.1. Product groups in PC-TAS partly or fully covered in this study.

Group code	Product group
AA	Live animals
AB	Meat and edible offal, fresh, chilled, frozen
AC	Meat products
AG	Dairy products and eggs
AY	Products of animal origin, edible, not else specified
AZ	Products of animal origin, not edible, not else specified
BA	Fruit and vegetables
BB	Nuts and fruit kernels
BC	Spices and culinary herbs
BD	Coffee tea and mate
BE	Cereals
BF	Cereal products
BG	Starches
BH	Sugars and molasses
BK	Lac, gums, resins vegetables saps/extracts
BN	Tobacco, tobacco products and substitutes
BY	Vegetable products, chiefly for food use, not else specified
CB	Fruit and vegetable juices and concentrates
CD	Alcoholic beverages
CF	Cocoa and cocoa products
CZ	Animal feed not else specified
DA	Oil crops, including flours and meals
DB	Oil-cakes
DC	Oil and fats
HA	Hides and skins
HB	Leather and its products
HZ	Leather products not else specified
LA	Textile fibres

As various other data necessary for the present analysis are not readily available, we have selected 285 crop products and 123 livestock products from these 28 relevant product groups in PC-TAS. The various products and their product codes as used in PC-TAS are listed in Appendix IV. A number of products have been excluded in our analysis because of the absence of proper data sets. Not included for instance are cigars and cigarettes (part of group BN), synthetic fibres and wool (group LA), honey (group BH), mushrooms (group BA), alcoholic beverages such as whiskies and rum (group CD) some specific herbs and spices (group BC), reptile skins (group HA), reptile leathers (group HB), fish (group AY) and animal fats (group DC). Also not included are products such as feathers, dead animals, silk-worm cocoons and skin of birds (group AZ).

Cotton lint and garneted stock of cotton (group LA) are included. But it is worthwhile to mention that out of the large number of textile and related products (groups LA to LZ), only the products from group LA are covered in the present study. Textile products in the groups fibre waste (LB), textile yarns and threads (LC), textile fabrics (LD) etc. include products derived from different primary products such as cotton, artificial fibres, wool or a mix of different materials. These products are quite diverse in nature and are made up of from crop and artificial fibres which are not categorically specified in the trade database.

As for trade in industrial products, we have taken trade data from the World Trade Organisation (WTO, 2004a, b). Virtual water imports and exports are calculated by multiplying monetary data on international trade of industrial products by country specific data on the average virtual water content per dollar of industrial products. In this approach, all industrial products are included implicitly.

3.3. Input data

3.3.1. Population, land and water resources

Data on population per country have been taken from the World Bank online database (World Bank, 2004). Wherever the population data are not available in this database, data have been taken from FAO (FAOSTAT, 2004). The available data have been averaged for the period 1997-2001. Arable land is taken from FAO (FAOSTAT, 2004) for the period 1997-2001. Data on total renewable water resources and water withdrawals per country have also been taken from FAO (FAO, 2003f, g). The input data used have been summarised in Appendix V.

3.3.2. Gross national income, gross domestic production and added value in the industrial sector

The average gross national income (GNI in US$/yr) for the period 1998-2001 have been taken from the World Bank on-line database (World Bank, 2004). The gross domestic products are taken from the UNSD for current US$ (UNSD, 2004b) for the period of 1997-2001. Data for the countries missing in the list of UNSD are taken from IMF (2004).

Data on the contribution of the industrial sector to the gross domestic product have been taken from the on-line data source of the World Bank (2004). There are still some countries missing in the database. For these countries, the percentage share of industrial sector to the national GDP has been taken from the on-line data source of Frederick S. Pardee Centre (2004) and CIA (2004).

3.3.3. International trade data

Data on international trade in agricultural products have been taken from the Personal Computer Trade Analysis System (PC-TAS, 2004) of the International Trade Centre. Data on international trade in industrial products have been taken from the World Trade Organisation (WTO, 2004a,b).

The export data do not categorically specify whether they refer to the export of goods that are produced domestically or the re-export of imported products. The virtual water export *VWE* (m^3/yr) from a country is however made up of two components: virtual water export related to the export of domestic products (VWE_{dom}) and virtual water export related to the re-export of imported from other countries ($VWE_{re\text{-}export}$).

$$VWE = VWE_{dom} + VWE_{re-\text{export}} \tag{44}$$

We have assumed that the two components can be estimated based on the relative share of the use of domestic water resources and the virtual water import respectively.

$$VWE_{dom} = VWE \times \frac{AWU + IWW + DWW}{AWU + IWW + DWW + VWI} \tag{45}$$

$$VWE_{re-\text{export}} = VWE \times \frac{VWI}{AWU + IWW + DWW + VWI} \tag{46}$$

3.3.4. Climate data

The country average data for actual vapour pressure (e_a), daily maximum temperature (T_{max}), daily minimum temperature (T_{min}) and percentage cloud cover (1-*n/N*) for each country are taken from the on-line database of the Tyndall Centre for Climate Change and Research (Mitchell, 2003). The data available here are averages over the recent past (1961-90) for nine climate variables. The latitude (φ) and the average elevation (z) are taken for the capital of each country.

The data for wind speed (U_2) are taken from the database CLIMWAT (FAO, 2003b) for 140 countries and territories (Appendix II). For many countries climatic data are available for a number of climate stations. In this study we have taken the wind speed data for the climate station at or nearby the capital of the country. For countries where wind speed data were absent at all, we have taken data from the neighbouring country with similar climate. In some remaining cases we have adopted an average wind speed of 2 m/s as recommended by Allen *et al.* (1998).

3.3.5. Crop parameters

Countries in different climatic regions generally grow different crop varieties, which often have different crop parameters. The planting date also varies from country to country. The selection of crop type and suitable growing period for a particular type of crop in a country largely depends upon the climate of the country and many other factors like local customs, traditions, social structure, existing norms and policies. Here we have broadly assumed that the current practices adopted by the farmers are already best alternatives and the crops grown in similar climatic regions share similar crop parameters.

We have grouped countries into 10 different groups based on their climatic character. The different climates and their characteristics are presented in Table 3.2. This classification is based on the definition of different thermal climatic regions given by FAO (2003c).

Table 3.2. Criteria for thermal climate classification.

Climate region	Criteria[1]
Tropics	– All months with monthly mean temperatures, corrected to sea level, above 18° C.
Subtropics summer rainfall	– One or more months with monthly mean temperatures, corrected to sea level, below 18 °C but above 5 °C. – Northern hemisphere: rainfall in April-September ≥ rainfall in October-March. – Southern hemisphere: rainfall in October-March ≥ rainfall in April-September.
Subtropics winter rainfall	– One or more months with monthly mean temperatures, corrected to sea level, below 18 °C but above 5 °C. – Northern hemisphere: rainfall in October-March ≥ rainfall in April-September. – Southern hemisphere: rainfall in April-September ≥ rainfall in October-March.
Oceanic temperate	– At least one month with monthly mean temperatures, corrected to sea level, below 5° C and four or more months above 10° C. – Seasonality[2] less than 20° C.
Sub-continental temperate	– At least one month with monthly mean temperatures, corrected to sea level, below 5° C and four or more months above 10° C. – Seasonality[2] 20-35° C.
Continental temperate	– At least one month with monthly mean temperatures, corrected to sea level, below 5° C and four or more months above 10° C. – Seasonality[2] more than 35° C.
Oceanic boreal	– At least one month with monthly mean temperatures, corrected to sea level, below 5° C and more than one but less than four months above 10° C. – Seasonality[2] less than 20° C.
Sub-continental boreal	– At least one month with monthly mean temperatures, corrected to sea level, below 5° C and more than one but less than four months above 10° C. – Seasonality[2] 20-35° C.
Continental boreal	– At least one month with monthly mean temperatures, corrected to sea level, below 5° C and more than one but less than four months above 10° C. – Seasonality[2] more than 35° C.
Polar/Artic	– All months with monthly mean temperatures, corrected to sea level, below 10° C.

[1] *Source: FAO (2003c)*

[2] *Seasonality refers to the difference in mean temperature of the warmest and coldest month.*

Crop coefficients K_c for different crops are taken from FAO (Table 12 in Allen *et al.,* 1998). Whenever data for different crop parameters are not available for a particular crop type, the crops are first sorted out into different crop groups as defined by Allen *et al.* (1998) such as legumes, small vegetables, tropical tree and others. Then group average values of crop parameters for these crops are taken. The planting dates and cropping calendar are chosen based on the best available data. Crop calendars for some important crops are available for 90 countries in a study made by FAO (2003e). Data for crop lengths of different crops grown in different parts of the globe are available in FAO (Table 11 in Allen *et al., 1998*). The crop parameters per primary crop per climatic region are tabulated in Appendix VI.

3.3.6. Crop production volumes and crop yields

Data on average crop yield per primary crop (ton/ha) per country during 1997-2001 are taken from the on-line database of FAO (FAOSTAT, 2004) (Appendix VII). If crop yield is not available for that period we have used the global average crop yield for the concerned crop for the same period. The annual production data (ton/yr) for 164 primary crops are also taken from FAOSTAT (2004) for the period 1997-2001 and are presented in Appendix VIII.

3.3.7. Product fractions and value fractions of crop and livestock products

Crop and livestock products have been arranged in product trees, some of which are presented in Appendix IX. For each product, we have assumed a constant set of product fractions *pf* and value fractions *vf* across the globe. The product fractions for various crop and livestock products are derived from different commodity trees as defined in FAO (2003h) and production data from other sources. Based on the average world market price (Appendix IV) the value fraction *vf* for each product is calculated using Equation 34 and the results are presented in Appendix X. The virtual water content of a product is directly proportional to its *vf* and inversely proportional to its *pf*.

3.3.8. Process water requirements

The volume of process water requirement depends upon the type of product processed and the technology involved. For any specific product the processing water requirement is more or less the same across different countries. There are minor variations, based on the efficiency of water use depending on recycling percentage, cooling processes, etc. As the processing water is only a small part of the virtual water content of a crop or a livestock product, it will not affect the end results of the study if we assume one constant value for a specific product across the globe. The data for processing of livestock products are taken from Chapagain and Hoekstra (2003a). For crop products we have assumed that the processing water requirement is relatively small compared to the virtual water content of the primary crop and we have neglected these values in the subsequent calculation of the virtual water content of the processed crop products.

4. Water footprints

4.1. *Water needs by product*

4.1.1. *Reference evapotranspiration and crop water requirement*

The monthly average reference evapotranspiration ET_0 (mm/day) per country has been calculated as presented in Appendix XI. ET_0 is a climatic parameter expressing the evaporative power of the atmosphere. As we have taken country average climatic data for the calculation of ET_0 we see abrupt changes at the borders of different countries (Figure 4.1 and 4.2). It is clear that the countries near the tropics have in general higher reference evapotranspiration rates around the year. As a consequence of this climatic effect, the crop water requirements of crops grown in these areas are also generally high.

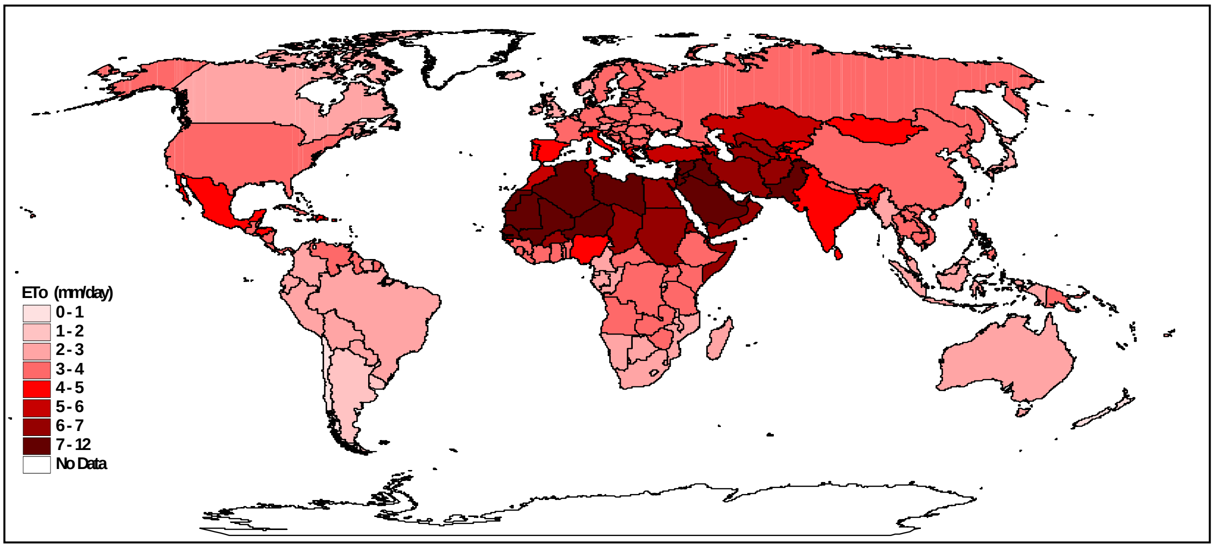


Figure 4.1. Monthly average reference evapotranspiration per country (mm/day) in June.

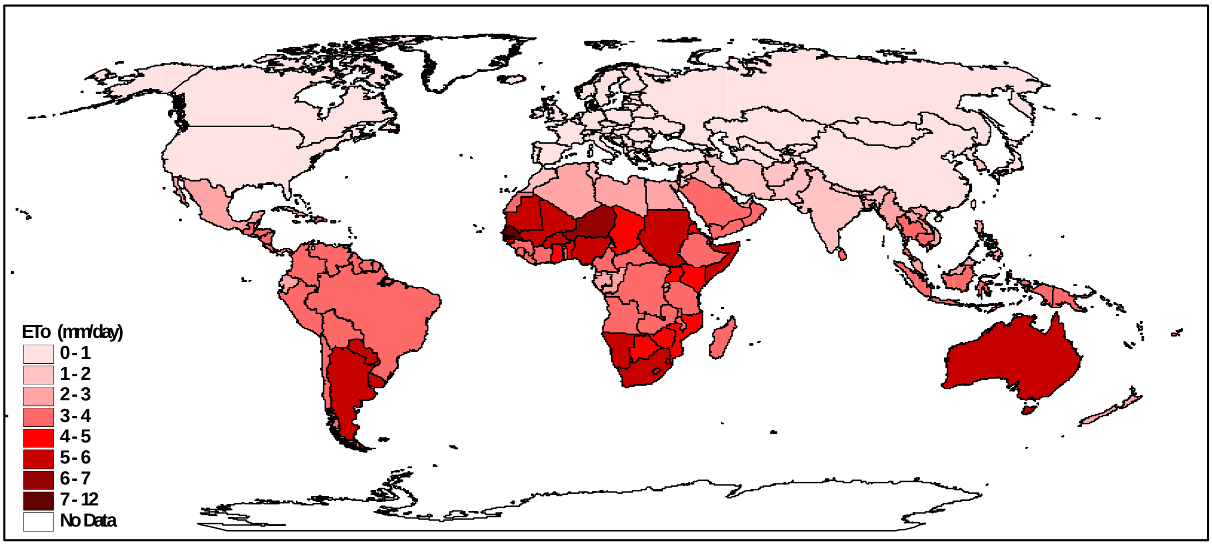


Figure 4.2. Monthly average reference evapotranspiration per country (mm/day) in December.

The crop water requirements are calculated based on the existing cropping patterns and the results are tabulated in Appendix XII. The results show that the crop water requirement of a specific crop may differ even for countries having the same range of ET_o. This may be either due to different planting dates of crops or different varieties of crops chosen. In turn, these factors are largely determined by the prevailing practices of crop cultivation.

4.1.2. Virtual water content of primary crops

The virtual water content of primary crops and the total volume of water used for crop production per crop per country are tabulated in Appendices XIII and XIV. The total volume of water used globally for crop production is 6390 Gm^3/yr. The global water withdrawal for irrigation is 2650 Gm^3/yr (FAO, 2003d). If we take the global water use efficiency as 40%, out of this 2650 Gm^3/yr only 1060 Gm^3/yr is used for the crop production at field level. This means that nearly 83% (5330 Gm^3/yr) of the total water use for crop production is green water. If we include the losses from the irrigation system, which is about 1590 Gm^3/yr, the total volume of water used in agriculture becomes 7980 Gm^3/yr, which means the share of green water will be 67%. It shows the significance of rain-fed agriculture related to the use of global water resources.

Rice has the largest share in the total volume water used for crop production. It consumes about 1359 Gm^3/yr which is about 21% of the total volume of water used for crop production. It is important to remember that we did not include irrigation losses in this estimate. The second largest water consumer is wheat, with about 793 Gm^3/yr (12%). The contribution of some major crops to the global water footprint related to food consumption is presented in Figure 4.3.

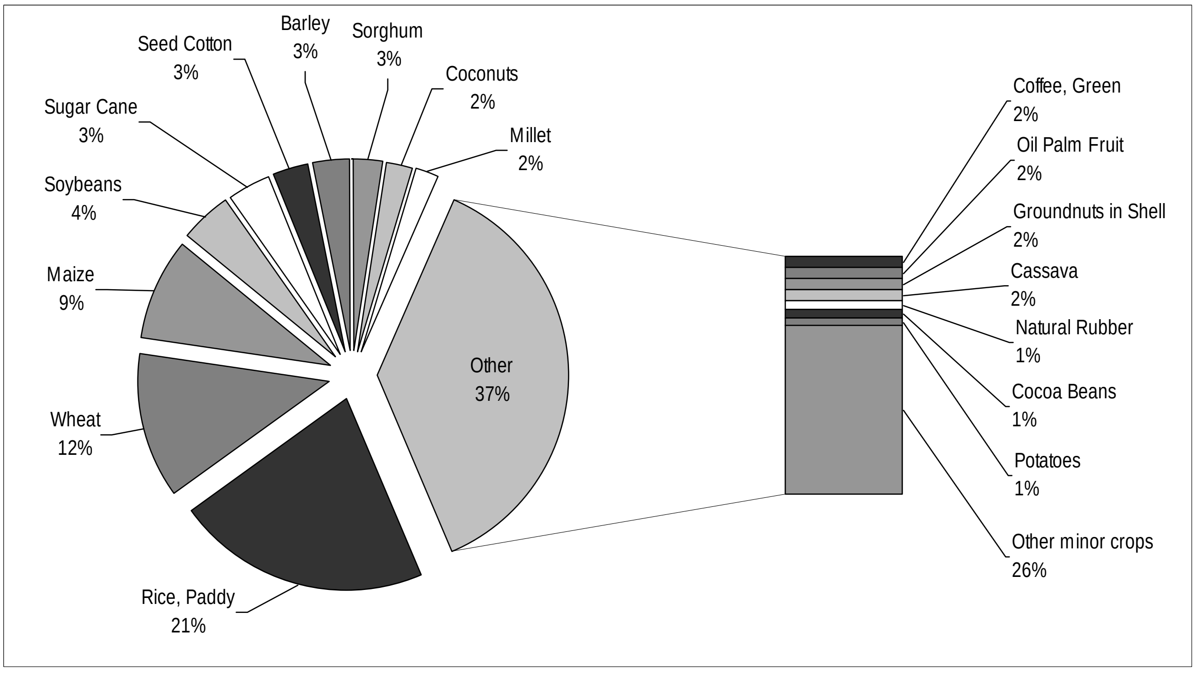


Figure 4.3. Contribution of different crops to the total volume of water used globally for crop production.

Global average virtual water content of different primary crops (m^3/ton) are calculated as the ratio of total volume of water used (m^3/yr) for the production of a crop around the globe to the total production (ton/yr) of that crop and the results are tabulated in Appendix XV. Although the total volume of rice production (593 million ton per year) is nearly equal to the wheat production (595 million ton per year), rice consumes much more water per ton of production. The difference is due to the higher evaporative demand for rice production and lower yields in comparison to wheat 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.

4.1.3. Virtual water content of processed crop and livestock products

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. This shows that if we talk about the virtual water content of different crops, we should be careful about the level of processing that the concerned crop product has passed through. The virtual water content of some selected crop and livestock products for a number of selected countries are presented in Table 4.1. For the complete set of data on virtual water content of crop and livestock products for a number of selected countries please see Appendix XVI.

Table 4.1. 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

	USA	China	India	Russia	Indonesia	Australia	Brazil	Japan	Mexico	Italy	Netherlands	World average[*]
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.*

In general livestock products have 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. Let us consider 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 litres of water (only for drinking and servicing). Producing the volume of feed requires about 15340 litres 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.

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 (=litres/kg). A consumer might be more interested to know how much water it consumes per unit of consumption. For example, what is the virtual water content of one cup of coffee, one glass of wine, one A4 sheet of paper or a slice of bread? Table 4.2 gives the global average virtual water content of some selected consumer goods expressed in water volumes per unit of product.

Table 4.2. 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 (medium sized, 500 g)	4100
1 sheet of A4-paper (80 g/m^2)	10

Product	Virtual water content (litres)
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

4.1.4. Virtual water content of industrial products

The global average virtual water content of industrial products is 80 litres per US$. In the USA, industrial products take nearly 100 litres per US$. In Germany and the Netherlands, average virtual water content of industrial products is about 50 litres per US$. Industrial products from Japan, Australia and Canada take only 10-15 litres per US$. In world's largest developing nations, China and India, the average virtual water content of industrial products is 20-25 litres per US$. Data for all countries analysed in this study are provided in Appendix XVII.

4.2. Virtual water flows and balances

4.2.1. International virtual water flows

The global virtual water flows during the period 1997-2001 in relation to the international trade in crop, livestock and industrial products added up to an average of 1625 Gm^3/yr (Table 4.3). A detailed overview of the flows per country is given in Appendix XVIII.

Table 4.3. Global sum of international virtual water flows per year (1997-2001).

Year	Gross virtual water flows (Gm^3/yr)			
	Related to trade of crop products	Related to trade of livestock products	Related to trade of industrial products	Total
1997	937	257	332	1526
1998	995	258	331	1584
1999	999	272	352	1623
2000	1041	302	401	1744
2001	961	293	393	1647
Average	987	276	362	1625

The major share (61%) of the virtual water flows between countries is related to international trade of crops and crop products. Trade in livestock products contributes 17% and trade in industrial products 22%. The total volume of international virtual water flows (1625 Gm^3/yr) includes virtual water flows that are related to re-export of imported products. The global volume of virtual water flows related to export of domestically produced products is 1197 Gm^3/yr (Table 4.4). With a total global water use of 7451 Gm^3/yr, this means that 16% of the global water use is not meant for domestic consumption but for export. In the agricultural sector, 15% of the water use is for producing export products; in the industrial sector this is 34%.

Table 4.4. International virtual water flows and global water use per sector. Period 1997-2001.

Gross virtual water flows				
	Related to trade of agricultural products (Gm^3/yr)	Related to trade of industrial products (Gm^3/yr)	Related to trade of domestic water (Gm^3/yr)	Total (Gm^3/yr)
Virtual water export related to export of domestically produced products	957	240	0	1197
Virtual water export related to re-export of imported products	306	122	0	428
Total virtual water export	1263	362	0	1625
Water use per sector				
	Agricultural sector	Industrial sector	Domestic sector	Total
Global water use (Gm^3/yr)	6391	716	344	7451
Water use in the world not used for domestic consumption but for export (%)	15	34	0	16

The major water exporters are the USA (229 Gm^3/yr), Canada (95 Gm^3/yr), France (79 Gm^3/yr), Australia (73 Gm^3/yr), China (73 Gm^3/yr), Germany (70 Gm^3/yr), Brazil (68 Gm^3/yr), the Netherlands (58 Gm^3/yr) and Argentina (51 Gm^3/yr). The major water importers are the USA (176 Gm^3/yr), Germany (106 Gm^3/yr), Japan (98 Gm^3/yr), Italy (89 Gm^3/yr), France (72 Gm^3/yr), the Netherlands (69 Gm^3/yr), UK (64 Gm^3/yr) and China (63 Gm^3/yr). The top-fifteen countries in terms of gross virtual water export and gross virtual water import for the period 1997-2001 are presented in Table 4.5.

Table 4.5. Top-15 of gross virtual water exporters and top-15 of gross virtual water importers. Period: 1997-2001.

Top gross exporters		Rank	Top gross importers	
Countries	Gross export (Gm^3/yr)		Countries	Gross import (Gm^3/yr)
USA	229.3	1	USA	175.8
Canada	95.3	2	Germany	105.6
France	78.5	3	Japan	98.2
Australia	73.0	4	Italy	89.0
China	73.0	5	France	72.2
Germany	70.5	6	Netherlands	68.8
Brazil	67.8	7	United Kingdom	64.2
Netherlands	57. 6	8	China	63.1
Argentina	50.6	9	Mexico	50.1
Russia	47.7	10	Belgium-Luxembourg	47.1
Thailand	42.9	11	Russia	46.1
India	42.6	12	Spain	45.0
Belgium-Luxembourg	42.2	13	Korea Rep.	39.2
Italy	38.2	14	Canada	35.4
Cote d'Ivoire	35.1	15	Indonesia	30.4

In order to show virtual water flows between different world regions, the world has been classified into 13 world regions: North America, Central America, South America, Eastern Europe, Western Europe, the Middle East, North Africa, Central Africa, Southern Africa, the Former Soviet Union, Central and South Asia, South-east Asia and Oceania. Gross virtual flows related to the international trade in agricultural products between and within regions in the period 1997-2001 are presented in Table 4.6. The single most important intercontinental water dependency is Central and South Asia (including China and India) importing 80 Gm^3/yr of virtual water from North America.

Table 4.6. Average annual gross virtual water flows between world regions related to the international trade in agricultural products in the period 1997-2001 (Gm^3/yr). The grey-shaded cells show the international virtual water flows within a region.

Importer Exporter	Central Africa	Central America	Central and South Asia	Eastern Europe	Former Soviet Union	Middle East	North Africa	North America	Oceania	South America	South-east Asia	Southern Africa	Western Europe	Total gross export
Central Africa	0.80	0.07	1.73	1.29	0.03	0.26	0.96	0.90	0.06	0.05	1.19	0.17	16.45	23
Central America	0.08	3.13	3.88	0.65	6.14	0.38	0.75	23.98	0.06	0.58	0.23	0.03	10.67	47
Central and South Asia	1.29	0.81	31.53	1.21	4.08	6.67	3.86	4.44	0.37	0.61	16.90	1.37	9.80	51
Eastern Europe	0.01	0.08	0.69	10.77	4.80	2.65	1.08	0.55	0.08	0.10	0.19	0.03	14.15	24
Former Soviet Union	0.01	0.07	3.06	4.47	16.67	5.38	1.26	0.05	0.00	0.30	0.41	0.00	10.54	26
Middle East	0.24	0.11	2.73	0.84	1.46	8.45	3.43	1.01	0.13	0.17	1.86	0.05	6.91	20
North Africa	0.10	0.24	7.09	6.15	2.11	4.32	5.87	8.37	0.17	2.29	3.49	0.52	63.22	98
North America	0.46	40.65	80.18	1.71	2.43	11.22	11.38	35.10	0.96	11.51	13.72	0.79	25.57	201
Oceania	0.34	1.24	29.32	0.33	0.33	6.22	2.13	11.33	12.63	0.67	14.64	1.11	7.76	75
South America	0.39	3.06	19.82	4.23	4.46	8.92	5.08	19.65	0.37	28.09	4.63	1.93	54.44	127
South-east Asia	1.96	0.50	35.57	2.43	1.52	7.75	8.00	10.89	2.49	0.93	26.87	2.54	18.14	93
Southern Africa	1.04	0.06	2.12	0.38	0.19	0.53	0.54	1.12	0.05	0.17	2.41	2.59	7.21	16
Western Europe	1.40	2.60	15.45	18.87	10.56	12.28	14.26	9.79	0.91	2.45	2.61	1.82	183.51	93
Total gross import	7	50	202	43	38	67	53	92	6	20	62	10	245	895

The gross virtual water flows between countries within a region have been calculated by summing up all virtual water imports of the countries of the region that originate from other countries in the same region. It can also be done by adding up virtual water exports of the countries in a region to the countries in the same region. Western Europe is the region with the biggest volume of internal virtual water flows (184 Gm^3/yr), followed by North America (35 Gm^3/yr), Central and South Asia (32 Gm^3/yr), South America (28 Gm^3/yr) and South-east Asia (27 Gm^3/yr).

4.2.2. National and regional virtual water balances

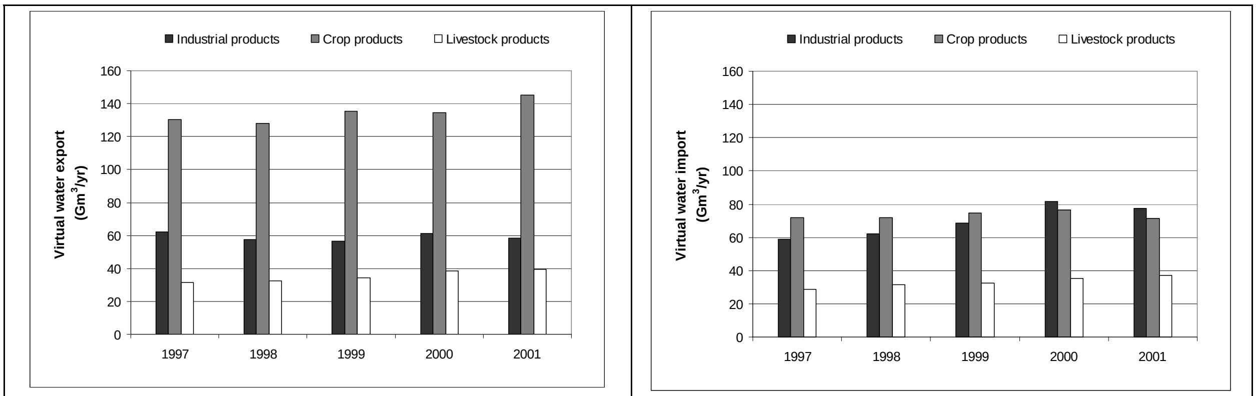
National virtual water flow balances are derived by subtracting the export volume from the import volume. The top-ten of net exporters and the top-ten of net importers of virtual water are shown in Table 4.7. Data for the full list of countries are presented in Appendix XVIII.

Table 4.7. Top-ten of net virtual water exporters and top-ten of net virtual water importers. Period 1997-2001.

Countries with net export	Virtual water flows (Gm^3/yr)			Rank	Countries with net import	Virtual water flows (Gm^3/yr)		
	Export	Import	Net export			Import	Export	Net import
Australia	73	9	64	1	Japan	98	7	92
Canada	95	35	60	2	Italy	89	38	51
USA	229	176	53	3	United Kingdom	64	18	47
Argentina	51	6	45	4	Germany	106	70	35
Brazil	68	23	45	5	South Korea	39	7	32
Ivory Coast	35	2	33	6	Mexico	50	21	29
Thailand	43	15	28	7	Hong Kong	28	1	27
India	43	17	25	8	Iran	19	5	15
Ghana	20	2	18	9	Spain	45	31	14
Ukraine	21	4	17	10	Saudi Arabia	14	1	13

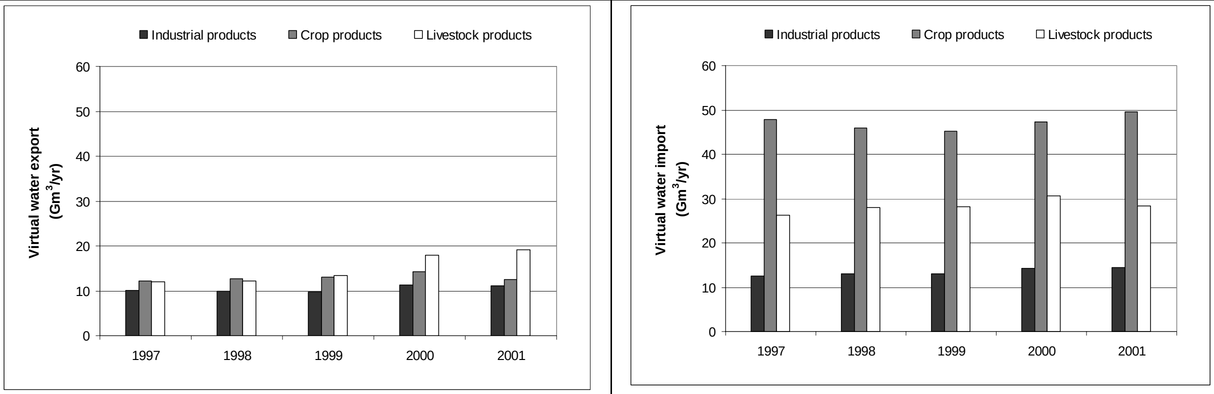
The calculations of national virtual water balances show that developed countries generally have a more stable virtual water balance than the developing countries. Countries that are relatively close to each other in terms of geography and development level can have a rather different virtual water balance. Germany, the Netherlands and the UK are net importers whereas France is a net exporter. USA and Canada are net exporter whereas Mexico is a net importer. Although USA has more than 3 times as much gross virtual water export as Australia, it is not at the top in the list of net exporters. The reason is that the USA has the largest gross import as well. Some countries, such as France, have large virtual water export (79 Gm^3/yr) but virtual water import at nearly the same scale (72 Gm^3/yr), putting them relatively low in the list of net exporters.

Each country has its own typical virtual water balance characteristics, which is illustrated in Figure 4.4 for four different countries: the USA, Italy, the Netherlands and China. The latter country for instance has net virtual water import in relation to trade in crop products, but net virtual water export in relation to trade in industrial products. In the USA we see the reverse. Italy is highly dependent on virtual water import in relation to all three major consumption categories (crop, livestock and industrial products). The Netherlands have an overall net import of virtual water but export virtual water in relation to export of livestock products.



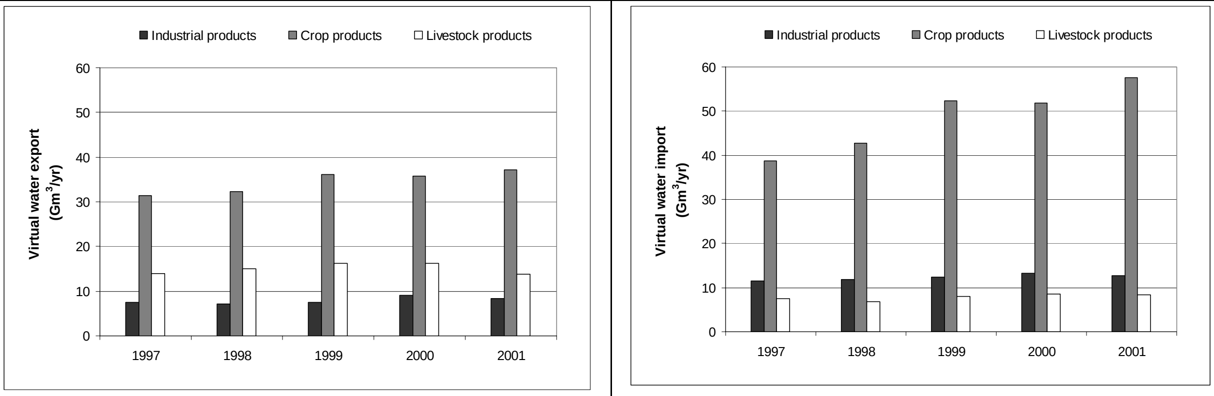
Gross virtual water export of the USA

Gross virtual water import of the USA



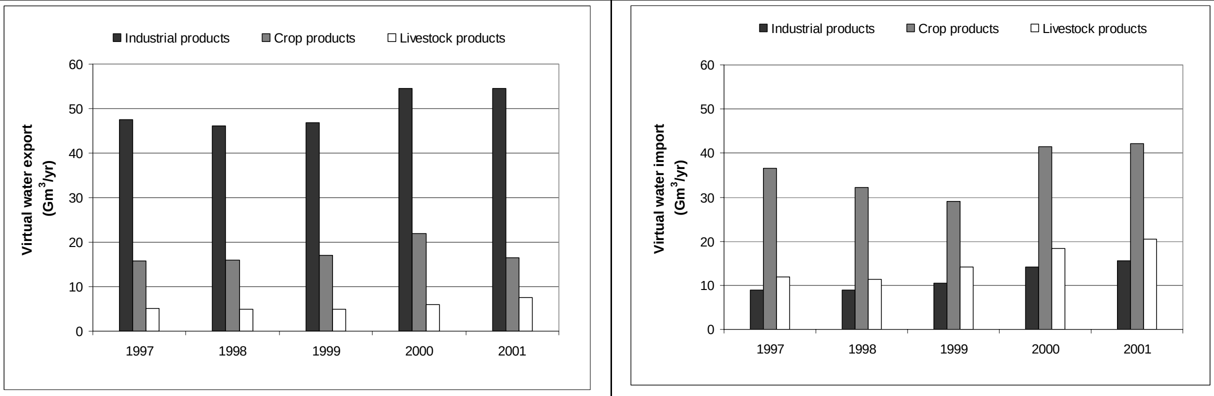
Gross virtual water export of Italy

Gross virtual water import of Italy



Gross virtual water export of the Netherlands

Gross virtual water import of the Netherlands



Gross virtual water export of China

Gross virtual water import of China

Figure 4.4. Annual gross virtual water exports and imports per consumption category for the USA, Italy, the Netherlands and China during the period 1997-2001.

Average national virtual water balances over the period 1997-2001 are shown in Figure 4.5. The green coloured countries in the map have net virtual water export, the red coloured ones net virtual water import. Figure 4.6 shows average virtual water balances over the period 1997-2001 at the level of 13 world regions. The figure also shows the biggest virtual water flows between the different regions of the world insofar related to trade in agricultural products. The regional analysis shows that the largest virtual water exporters are North America (109 Gm^3/yr) and South America (107 Gm^3/yr) and the largest importers are Western Europe (152 Gm^3/yr) and Central and South Asia (151 Gm^3/yr).

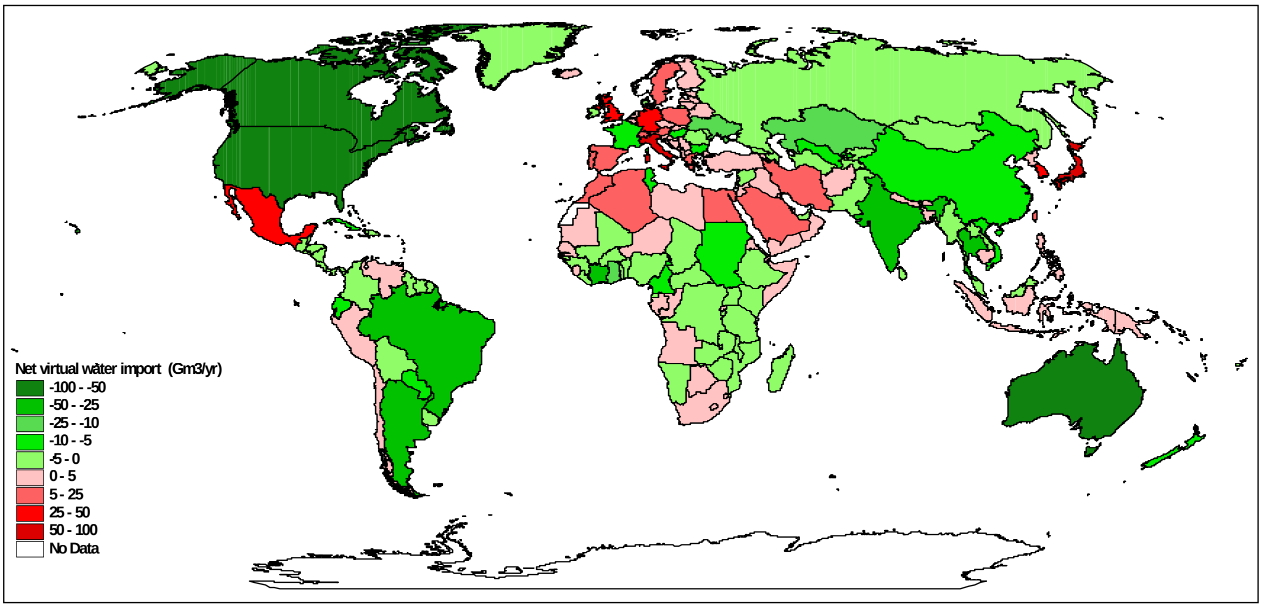


Figure 4.5. National virtual water balances related to the international trade of products. Period 1997-2001.

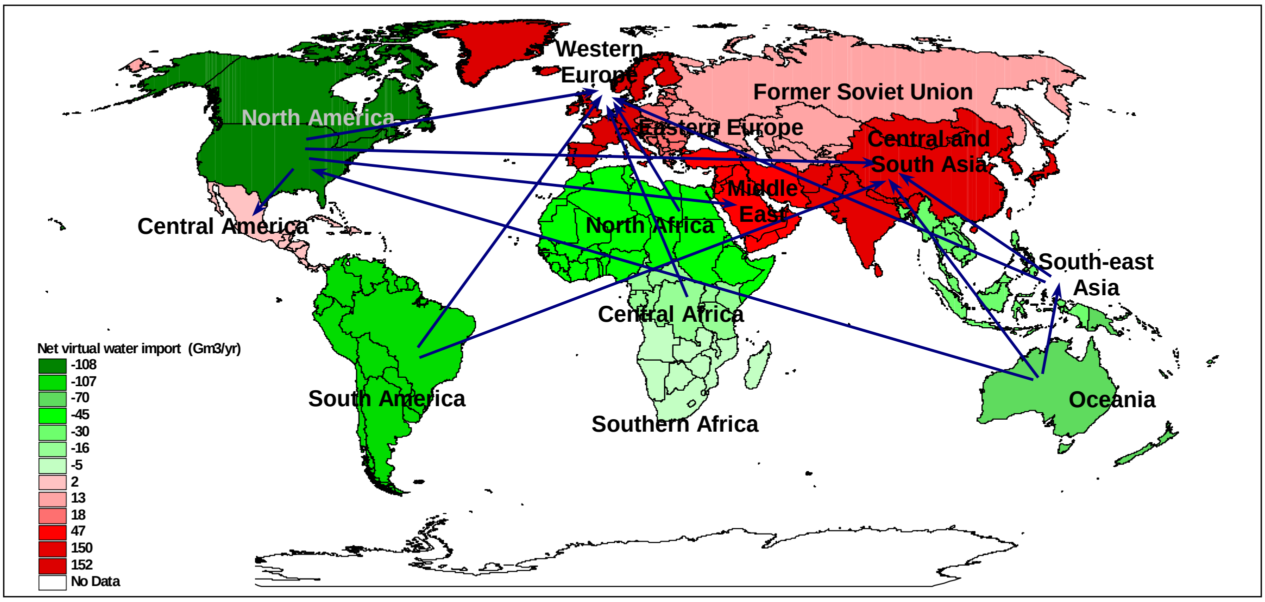


Figure 4.6. Regional virtual water balances and net interregional virtual water flows related to the trade in agricultural products. Period: 1997-2001. Only the biggest net flows (>10 Gm^3/yr) are shown.

4.2.3. Global virtual water flows by product

Bovine meat is the product with the single largest contribution to the global virtual water flows, followed by soybean and wheat. The volumes of virtual water flows by product are presented in Appendix XIX. The major products and their share to the total global virtual water flows are shown in the Figure 4.7.

Although the global volume of water consumption for producing rice is more than for wheat the global virtual water flows related to the international trade of wheat are higher than for rice. However for some major rice exporting countries the use of domestic water resources for producing rice for export can be significant. For example, Thailand uses 28 Gm^3/yr of water from its domestic resources to produce rice for export, which is equal to 7% of the total renewable water resources.

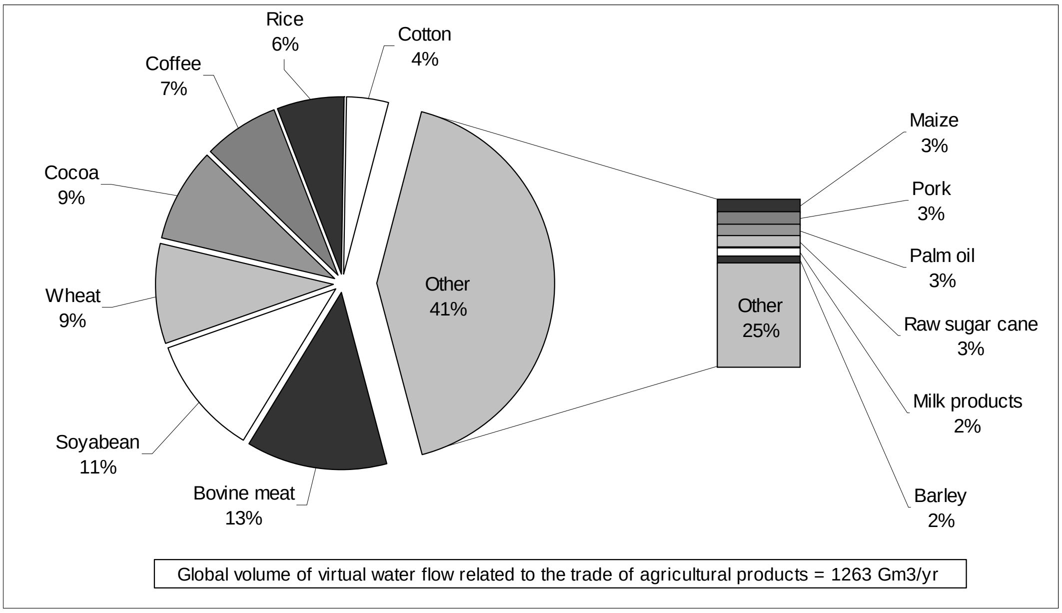


Figure 4.7. Contribution of various agricultural products to the global average virtual water flows related to the international trade of agricultural products over the period 1997-2001.

It varies very much from country to country which products and product groups contribute most to the ingoing and outgoing virtual water flows (Table 4.8). The products behind the gross virtual water exports are generally different from the products behind the virtual water imports, which means that ingoing and outgoing virtual water flows can not simply be crossed out against each other. For example, in the USA 48% of the gross virtual water export related to crop trade is from the export of oil crops and oils and 38% in the form of cereal products, whereas 50% of its gross virtual water import related to crop trade is from the import of coffee, tea and cocoa products. China is a net exporter of virtual water in terms of cereal products (8.5 Gm^3/yr export and 5.8 Gm^3/yr import), but a net importer with respect to the oil crop, oil-cakes and oil products (3.1 Gm^3/yr export and 24.4 Gm^3/yr import). China is a net exporter of industrial products with 38.3 Gm^3/yr which makes it a net exporter country. France has nearly balanced virtual water flows with respect to the trade in crop products, but it mainly exports cereals (24 Gm^3/yr) and imports coffee, tea, cocoa, oil crops and oil-cakes (30.5 Gm^3/yr).

In the Netherlands the main products responsible for the import and export are from the same crop categories; coffee, tea, cocoa, oil crops, oil-cakes and oil products. With the trade of products from these categories, it imports 37 Gm^3/yr and export 29 Gm^3/yr. A large part of export is re-export of imported products (the Netherlands even does not produce products like coffee, tea and cocoa). Australia mainly exports cereals (31 Gm^3/yr) and imports coffee, tea, cocoa, oil crops, oil-cakes and oil products (3.0 Gm^3/yr). Australia also has a large net export of livestock products, which is 26 Gm^3/yr. Thailand uses 28 Gm^3/yr for producing rice for export, which is quite significant if compared to the total agricultural water withdrawal in Thailand, which is 81 Gm^3/yr.

Table 4.8. The contributions of individual products or product categories to the virtual water flows of a nation and their main trade partners for some selected nations. Period 1997-2001.

			USA		France		Australia		China		Canada		Netherlands		Thailand		India		Italy	
Export (Gm^3/yr)	Crop	Gross export		134.6		43.4		46.1		17.4		48.3		34.5		38.4		32.4		12.9
		Main crop categories	Oilcrops/oil-cakes/oil	65.9	Cereals	23.9	Cereals	31.1	Cereals	8.5	Cereals	31.1	Oilcrops/oil-cakes/oil	14.5	Cereals	29.2	Oilcrops/oil-cakes/oil	17.3	Cereals	4.2
			Cereals	50.8	Sugar/molasses	6.0	Oilcrops/oil-cakes/oil	6.1	Oilcrops/oil-cakes/oil	2.9	Oilcrops/oil-cakes/oil	13.4	Coffee/Tea/Cocoa	14.4	Sugar/molasses	5.1	Cereals	7.8	Oilcrops/oil-cakes/oil	3.6
			Textile fibres	9.1	Oilcrops/oil-cakes/oil	5.9	Sugar/molasses	4.3	Fruit/Veg/Juices	2.6	Fruit/Veg/Juices	2.4	Cereals	2.3	Fruit/Veg/Juices	2.5	Coffee/Tea	3.2	Fruit/Veg/Juices	2.0
							Textile fibres	3.0	Coffee/Tea/Cocoa	1.8			Fruit/Veg/Juices	1.6			Textile fibres	1.5	Coffee/Tea/Cocoa	1.2
									Textile fibres	0.4							Spices etc	1.0		
		Main crops	Soybean	56.9	Wheat	14.7	Sugar	16.4	Maize	4.1	Wheat	25.3	Cocoa	14.0	Rice	27.9	Soybean	8.8	Olive	2.8
			Maize	21.0	Sugar	4.6	Rice	8.5	Rice	3.6	Soybean	1.4	Soybean	6.9	Sugar	4.8	Rice	7.2	Rice	1.6
			Wheat	15.0	Maize	3.5	Wheat	4.3	Soybean	1.5	Barley	2.0					Tea	1.3	Coffee	0.9
			Cotton	9.1					Sugar	0.7							Coffee	1.9		
			Rice	4.2					Wheat	0.4										
		Main partners	Mexico	21.2	Bel-lux	8.2	P.NewGunea	7.9	Korea Rep	3.4	USA	11.7	Germany	8.3	Indonesia	4.8	Indonesia	2.5	Germany	1.9
			Japan	21.0	Italy	4.6	Japan	7.1	Japan	2.0	Mexico	2.9	Bel-lux	5.6	Malaysia	2.7	China	2.1	France	1.7
			China	8.9	Germany	4.5	China	4.2	Indonesia	1.4	Japan	6.7	UK	4.7	Iran	2.6	USA	2.0	USA	1.6
			Canada	8.1	Netherlands	4.2	Indonesia	4.2	Malaysia	1.2	Iran	3.7	France	2.5	Japan	2.3	Saudi Arabia	2.0	Yemen	0.7
			Taiwan	7.3	Spain	3.4	Iran	3.3			China	3.4			China	2.2	Korea	1.8	UK	0.6
					UK	2.9	Malaysia	2.2			Algeria	2.1			USA	1.9	Japan	1.6		
	livestock	Gross export		35.5		13.2		26.4		5.6		17.4		15.1		2.9		3.4		14.9
		Main livestock product groups	Meat and ediable offals	17.0	Meat and ediable offals	4.8	Meat and ediable offals	17.2	Hides/skins/leather	2.7	Meat and ediable offals	8.3	Meat and ediable offals	7.5			Meat and ediable offals	2.4	Hides/skins/leather	10.3
			Hides/skins/leather	10.0	Dairy products	3.3	Hides/skins/leather	3.3	Meat and ediable offals	0.6	Live animals	5.8	Dairy products	1.5			Hides/skins/leather	0.7	Meat and ediable offals	2.0
					Live animals	2.5	Dairy products	2.2	Live animals	0.6	Hides/skins/leather	2.0	Live animals	1.1			Dairy products	0.3	Dairy products	1.2
					Hides/skins/leather	1.3	Live animals	1.9					Hides/skins/leather	0.9					Live animals	0.2
		Main animal categories	Bovine	25.1	Bovine	6.3	Bovine	20.0	Bovine	2.6	Bovine	11.8	Bovine	4.4			Bovine	2.8	Bovine	11.0
			Swine	3.4	Dairy cow	3.2	Dairy cow	2.2	Swine	1.0	Swine	4.4	Swine	5.8			Laying hens	0.3	Swine	0.8
			Dairy cow	1.0	Swine	2.4	Sheep	2.1	Dairy cow	0.3			Dairy cow	2.9					Dairy cow	0.7
	Industrial products			59.0		21.9		0.5		49.9		29.6		7.9		1.7		6.7		10.4
Import (Gm^3/yr)	Crop	Gross import		73.0		40.6		3.9		36.3		16.2		48.6		9.8		13.9		47.2
		Main crop categories	Coffee/Tea/Cocoa	36.8	Coffee/Tea/Cocoa	15.7	Coffee/Tea/Cocoa	1.8	Oilcrops/oil-cakes/oil	24.4	Coffee/Tea/Cocoa	5.4	Coffee/Tea/Cocoa	18.6	Oilcrops/oil-cakes/oil	4.4	Oilcrops/oil-cakes/oil	8.0	Oilcrops/oil-cakes/oil	21.4
			Oilcrops/oil-cakes/oil	11.2	Oilcrops/oil-cakes/oil	14.8	Oilcrops/oil-cakes/oil	1.4	Cereals	5.8	Oilcrops/oil-cakes/oil	3.4	Oilcrops/oil-cakes/oil	18.2	Textile fibres	3.7	Fruit/Veg/Juices	1.7	Coffee/Tea/Cocoa	10.2
			Cereals	9.3	Fruit/Veg/Juices	3.7	Cereals	0.3	Textile fibres	2.2	Sugar/Molasses	3.3	Cereals	6.5	Cereals	1.3	Cereals	1.4	Cereals	8.5
			Fruit/Veg/Juices	7.0	Cereals	2.6					Cereals	1.8					Spices etc	0.5	Textile fibres	3.3
					Textile fibres	1.2					Fruit/Veg/Juices	1.4								
											Textile fibres	0.6								
		Main crops	Coffee	20.0	Cocoa	8.9			Soyabean	14.8	Sugar	3.2	Cocoa	15.9	Soyabean	3.6	Palm oil	5.0	Olive	13.3
			Cocoa	15.7	Coffee	6.7			Barley	2.5	Cocoa	2.9	Soyabean	8.3	Cotton	3.6	Wheat	1.3	Coffee	6.9
			Wheat	3.6	Soyabean	5.4			Sugar	1.6	Coffee	2.3	Wheat	3.2	Wheat	1.0	Soyabean	0.8	Wheat	6.7
			Oats	2.5	Rice	1.3			Wheat	1.5	Soyabean	2.2	Coffee	2.5			Sugar	0.9	Cotton	3.5
			Rice	1.7					Rice	1.5	Maize	0.9	Rice	0.7					Cocoa	3.3
											Rice	0.8							Soyabean	3.3
		Main partners	Canada	11.7	Cote d'ivore	5.1			USA	8.9	USA	8.1	Cote d'Ivore	5.7	USA	2.2	Malaysia	3.3	Tunisia	7.7
			Mexico	8.3	Brazil	4.2			Malaysia	2.6	Brazil	1.0	Germany	4.5	India	1.4	Indonesia	2.1	France	4.6
			Brazil	5.4	Spain	3.1			Brazil	2.6			USA	4.2	Australia	0.9	Argentina	1.3	Spain	4.2
			Cote d'ivore	4.7	India	1.5			India	2.1			France	4.2	Argentina	1.0	Pakistan	0.6	Brazil	2.1
			Colombia	3.5	USA	1.0			Thailand	2.2			Ghana	3.6					Greece	2.1
			India	2.0					Australia	4.3			Brazil	3.4					Argentina	1.9
			Thailand	1.9					Argentina	2.9									USA	1.7
	Livestock	Gross import		33.0		11.8		0.7		15.2		5.0		7.9		1.8		0.3		28.3
		Main livestock product groups	Meat and ediable offals	14.6	Meat and ediable offals	6.4			Hides/skins/leather	13.1	Meat and ediable offals	2.9	Dairy cow	2.4					Hides/skins/leather	11.6
			Live animals	9.1	Dairy products	2.1			Meat and ediable offals	0.8	Hides/skins/leather	0.7	Meat and ediable offals	2.3					Meat and ediable offals	8.4
			Hides/skins/leather	6.0	Hides/skins/leather	0.9					Live animals	0.5	Live animals	0.8					Live animals	4.0
			Dairy products	0.9	Live animals	0.6							Hides/skins/leather	0.8					Dairy products	3.3
		Main animal categories	Bovine	25.0	Bovine	4.7			Bovine	11.8	Bovine	3.9	Bovine	3.2					Bovine	17.4
			Swine	3.4	Swine	2.4			Swine	0.7	Swine	0.3	Dairy cow	2.4					Swine	4.8
			Dairy cow	0.9	Dairy cow	2.1			Sheep	0.6	Dairy cow	0.2	Swine	0.8					Dairy cow	3.3
			Horse	0.4	Sheep	0.7													Sheep	1.1
	Industrial products			70.0		19.8		4.4		11.6		14.3		12.3		3.6		2.9		13.5
Total gross export (Gm^3/yr)				229.1		78.5		73.0		72.9		95.3		57.5		43.0		42.5		38.2
Total gross import (Gm^3/yr)				176.0		72.2		9.0		63.1		35.5		68.8		15.2		17.1		89.0
Net import (Gm^3/yr)				-53.1		-6.3		-64.0		-9.8		-59.8		11.3		-27.8		-25.4		50.8

4.3. *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 4.8. The data are shown in Table 4.9 for hundred selected countries and in Appendix XX for all countries considered in this study.

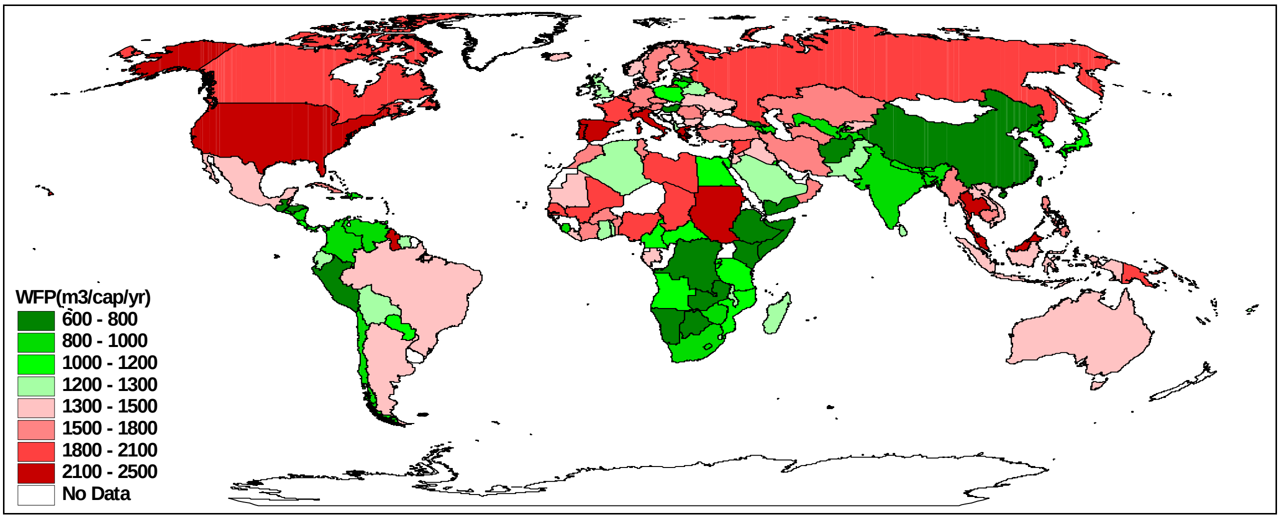


Figure 4.8. Average national water footprint per capita (m^3/capita/yr). Green means that the nation's water footprint is equal to or smaller than global average. Countries with red have a water footprint beyond the global average.

The size of the global water footprint is largely determined by the consumption of food and other agricultural products (Figure 4.9). Our estimate of the contribution of agriculture to the total water use is even bigger than most other statistics due to the inclusion of green water use (use of soil water).

Table 4.9. Composition of the water footprint for some selected countries. Period: 1997-2001.

Country	Population	Use of domestic water resources					Use of foreign water resources			Water footprint		Water footprint by consumption category				
		Domestic water withdrawal	Crop evapotranspiration*		Industrial water withdrawal		For national consumption		For re-export of imported products	Total	Per capita	Domestic water	Agricultural goods		Industrial goods	
			For national consumption	For export	For national consumption	For export	Agricultural goods	Industrial goods				Internal water footprint	Internal water footprint	External water footprint	Internal water footprint	External water footprint
		Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	m^3/cap/yr	m^3/cap/yr	m^3/cap/yr	m^3/cap/yr	m^3/cap/yr	m^3/cap/yr
Afghanistan	26179398	0.34	16.47	0.19	0.001		0.45	0.03	0.01	17.29	660	13	629	17	0	1
Algeria	30169250	1.23	22.77	0.32	0.494	0.25	11.91	0.29	0.31	36.69	1216	41	755	395	16	10
Argentina	36806250	4.68	41.31	48.03	2.328	0.30	1.81	1.53	2.30	51.66	1404	127	1122	49	63	42
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
Austria	8103235	0.76	2.98	1.89	1.070	0.29	4.66	3.55	3.91	13.02	1607	94	368	575	132	438
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
Belgium-Lux.	10659200	1.09	2.29	3.26	0.382	7.29	14.90	0.54	31.66	19.21	1802	103	215	1398	36	51
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
Bulgaria	8125750	0.37	9.50	1.92	0.048	9.27	1.42	0.00	0.66	11.33	1395	45	1169	174	6	0
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
Colombia	41919368	5.31	23.08	9.40	0.358	0.04	4.60	0.70	1.96	34.05	812	127	551	110	9	17
Congo, DR	50264530	0.20	36.16	0.79	0.058		0.39	0.08	0.01	36.89	734	4	719	8	1	2
Côte d'Ivoire	15792145	0.19	26.71	33.83	0.077	0.02	0.96	0.13	1.24	28.06	1777	12	1692	61	5	8
Denmark	5329750	0.38	2.36	6.31	0.296	0.03	2.18	2.46	6.08	7.68	1440	72	442	409	56	461
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
Ethiopia	63540513	0.13	42.22	2.22	0.104	0.00	0.33	0.09	0.02	42.88	675	2	664	5	2	1
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
Ghana	19082858	0.15	23.44	18.81	0.054	0.00	0.86	0.16	0.70	24.67	1293	8	1229	45	3	8
Greece	10550968	0.83	14.80	3.35	0.775	0.08	7.18	1.62	1.79	25.21	2389	79	1403	680	73	154
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

Country	Population	Use of domestic water resources					Use of foreign water resources			Water footprint		Water footprint by consumption category				
		Domestic water withdrawal	Crop evapotranspiration*		Industrial water withdrawal		For national consumption		For re-export of imported products	Total	Per capita	Domestic water	Agricultural goods		Industrial goods	
			For national consumption	For export	For national consumption	For export	Agricultural goods	Industrial goods				Internal water footprint	Internal water footprint	External water footprint	Internal water footprint	External water footprint
		Gm³/yr	Gm³/yr	Gm³/yr	Gm³/yr	Gm³/yr	Gm³/yr	Gm³/yr	Gm³/yr	Gm³/yr	m³/cap/yr	m³/cap/yr	m³/cap/yr	m³/cap/yr	m³/cap/yr	m³/cap/yr
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
Iran	63201525	4.68	78.58	3.18	0.984	0.60	17.90	0.51	1.03	102.65	1624	74	1243	283	16	8
Iraq	23034540	1.32	23.86	0.63	2.055		3.10	0.58	0.08	30.92	1342	57	1036	135	89	25
Israel	6166040	0.47	1.63	0.20	0.112	0.00	4.28	2.09	0.59	8.58	1391	75	264	694	18	339
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
Kazakhstan	15191620	0.59	24.87	7.92	1.147	4.58	0.29	0.06	0.33	26.96	1774	39	1637	19	76	4
Kenya	29742440	0.44	18.63	4.35	0.079	0.01	1.92	0.16	0.47	21.23	714	15	626	65	3	5
Korea, DPR	22213458	1.68	12.76	0.04	2.268		1.97	0.10	0.01	18.78	845	75	574	89	102	4
Korea, Rep	46813750	6.42	12.34	1.53	2.256	0.56	27.50	6.69	5.06	55.20	1179	137	264	587	48	143
Malaysia	22990590	1.43	36.58	18.47	0.867	0.90	12.73	2.28	8.81	53.89	2344	62	1591	554	38	99
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
Morocco	28472000	0.81	35.99	1.33	0.224	0.04	6.07	0.51	0.31	43.60	1531	28	1264	213	8	18
Myanmar	47451298	0.34	73.89	1.53	0.149		0.94	0.17	0.02	75.49	1591	7	1557	20	3	4
Nepal	22772793	0.27	18.35	0.19	0.031	0.00	0.60	0.08	0.01	19.33	849	12	806	26	1	4
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
Nigeria	125374700	1.41	240.38	8.54	0.383	0.30	5.59	0.31	0.43	248.07	1979	11	1917	45	3	2
Norway	4474000	0.45	1.09	0.17	1.032	0.43	2.42	1.57	1.02	6.56	1467	101	244	541	231	350
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
Peru	25752968	1.47	12.59	1.82	1.379	0.32	4.21	0.37	0.69	20.02	777	57	489	163	54	14
Philippines	75749645	4.50	99.09	7.61	0.805	1.69	11.74	0.71	2.40	116.85	1543	59	1308	155	11	9
Poland	38653288	1.85	21.62	2.78	6.890	4.15	10.41	1.85	2.45	42.62	1103	48	559	269	178	48

Country	Population	Use of domestic water resources					Use of foreign water resources			Water footprint		Water footprint by consumption category				
		Domestic water withdrawal	Crop evapotranspiration*		Industrial water withdrawal		For national consumption		For re-export of imported products	Total	Per capita	Domestic water	Agricultural goods		Industrial goods	
			For national consumption	For export	For national consumption	For export	Agricultural goods	Industrial goods				Internal water footprint	Internal water footprint	External water footprint	Internal water footprint	External water footprint
		Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	Gm^3/yr	m^3/cap/yr	m^3/cap/yr	m^3/cap/yr	m^3/cap/yr	m^3/cap/yr	m^3/cap/yr
Portugal	9997250	1.09	8.00	1.47	1.411	0.62	10.55	1.59	2.64	22.63	2264	109	800	1055	141	159
Romania	22450998	2.04	29.03	2.51	3.527	4.75	3.99	0.34	0.80	38.92	1734	91	1293	178	157	15
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
Saudi Arabia	20503670	1.61	10.42	0.42	0.181	0.01	12.11	1.58	0.62	25.90	1263	78	508	591	9	77
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
Spain	40417948	4.24	50.57	17.44	5.567	1.73	27.11	6.50	11.37	93.98	2325	105	1251	671	138	161
Sri Lanka	18335500	0.25	21.72	2.29	0.165	0.09	1.32	0.24	0.26	23.69	1292	14	1185	72	9	13
Sudan	30832808	0.89	66.62	7.47	0.189	0.04	0.48	0.07	0.07	68.25	2214	29	2161	15	6	2
Sweden	8868050	1.07	4.49	1.42	1.166	0.45	4.52	3.12	2.62	14.37	1621	121	507	509	132	352
Switzerland	7165250	0.45	0.97	0.23	1.057	0.33	5.59	3.98	2.56	12.05	1682	63	136	780	148	555
Tanzania	33299168	0.11	36.39	3.15	0.024	0.00	0.90	0.08	0.08	37.51	1127	3	1093	27	1	3
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
Turkey	66849750	5.38	84.05	9.81	2.731	1.07	13.68	2.11	2.43	107.95	1615	80	1257	205	41	32
Turkmenistan	5184250	0.38	8.39	1.07	0.118	0.05	0.18	0.07	0.05	9.14	1764	74	1619	36	23	13
Ukraine	49700750	4.60	54.14	10.09	3.673	9.71	2.72	0.26	1.21	65.40	1316	93	1089	55	74	5
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
Uzbekistan	24567500	2.68	18.93	6.24	1.151		1.06	0.23	0.35	24.04	979	109	771	43	47	9
Venezuela	23937750	2.80	12.42	1.28	0.360	0.13	4.86	0.70	0.76	21.14	883	117	519	203	15	29
Viet Nam	78020938	3.77	85.16	11.00	11.280		2.27	0.85	0.29	103.33	1324	48	1091	29	145	11
Global total/average	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.*

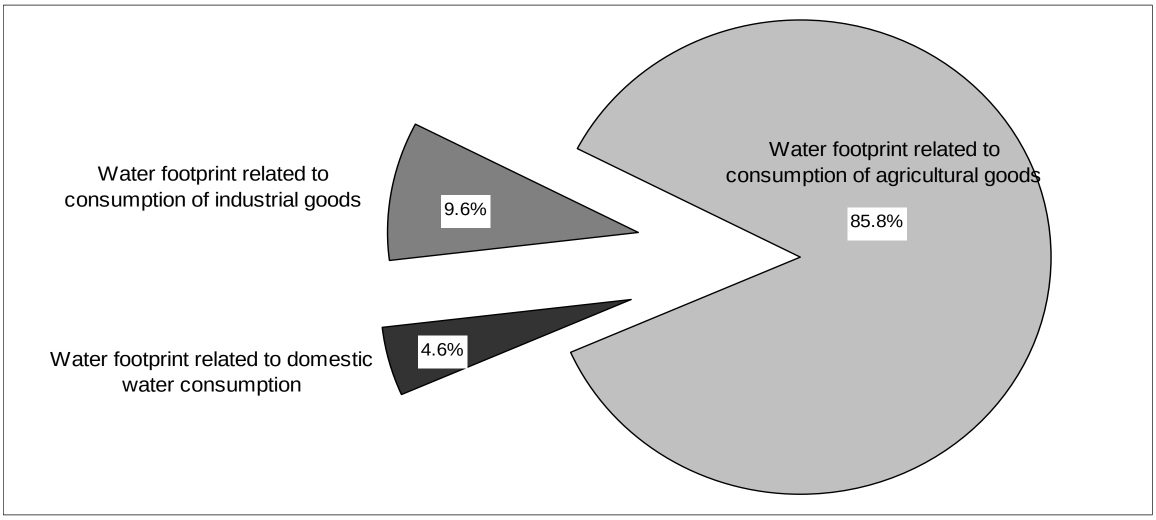


Figure 4.9. Global water footprint per consumption category.

The major factors determining the per capita water footprint of a country are:

- the average consumption volume per capita, generally related to gross national income per country,
- the consumption habits of the inhabitants of the country,
- climate, in particular evaporative demand, and
- agricultural practice.

In rich countries, people generally consume more goods and services, which immediately translate 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.

The influence of the various determinants varies from country to country. The water footprint of 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 4.10). 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.

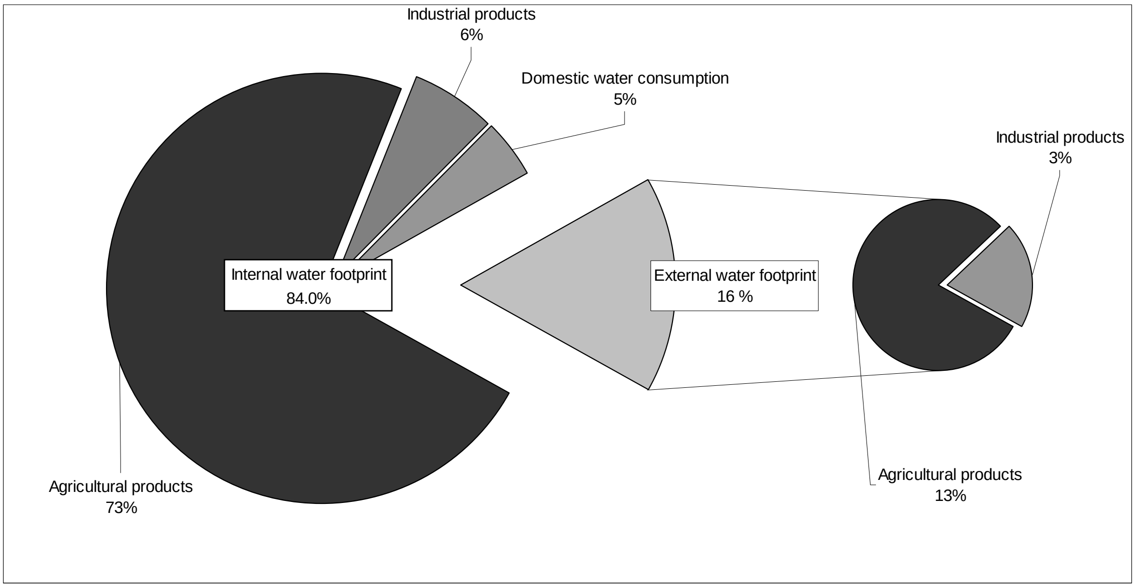


Figure 4.10. Contribution of different consumption categories to the global water footprint, with a distinction between the internal and external footprint.

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 4.11).

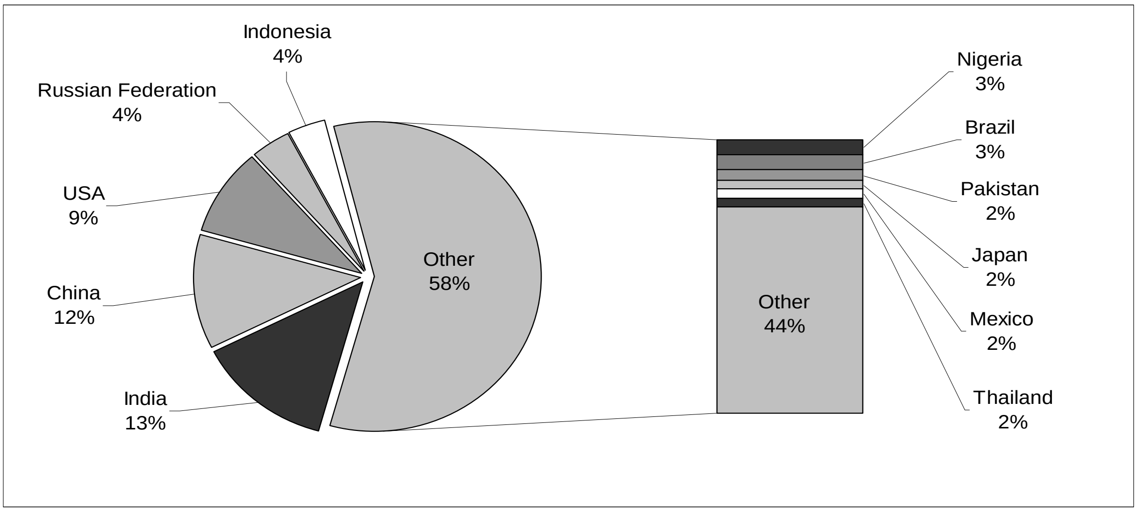


Figure 4.11. Contribution of different consumers to the global water footprint.

4.4. Details of the water footprint for a few selected countries

Both the size of the national water footprint and its composition differs between countries, as is illustrated in Figure 4.12. On the one end we see China with a relatively low water footprint per capita, and on the other end the USA. We see further that in the rich countries consumption of industrial goods has a relatively large contribution to the total water footprint if compared with developing countries.

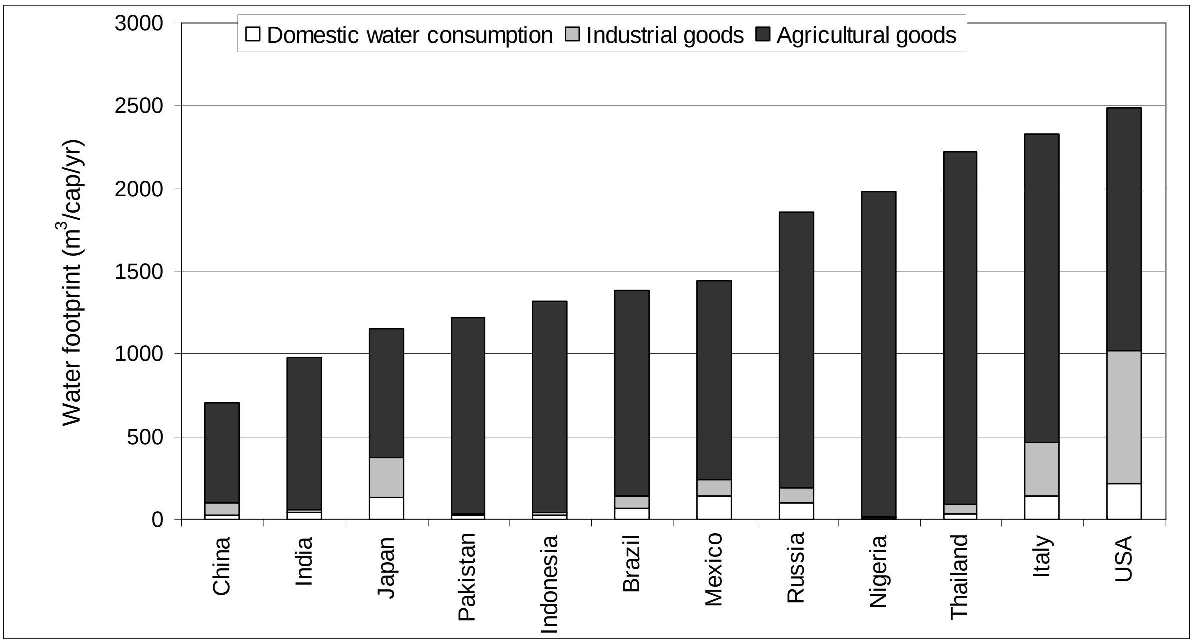


Figure 4.12. The national water footprint per capita and the contribution of different consumption categories for some selected countries.

The water footprints of the USA, China, India and Japan are presented in more detail in Figure 4.13. 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%).

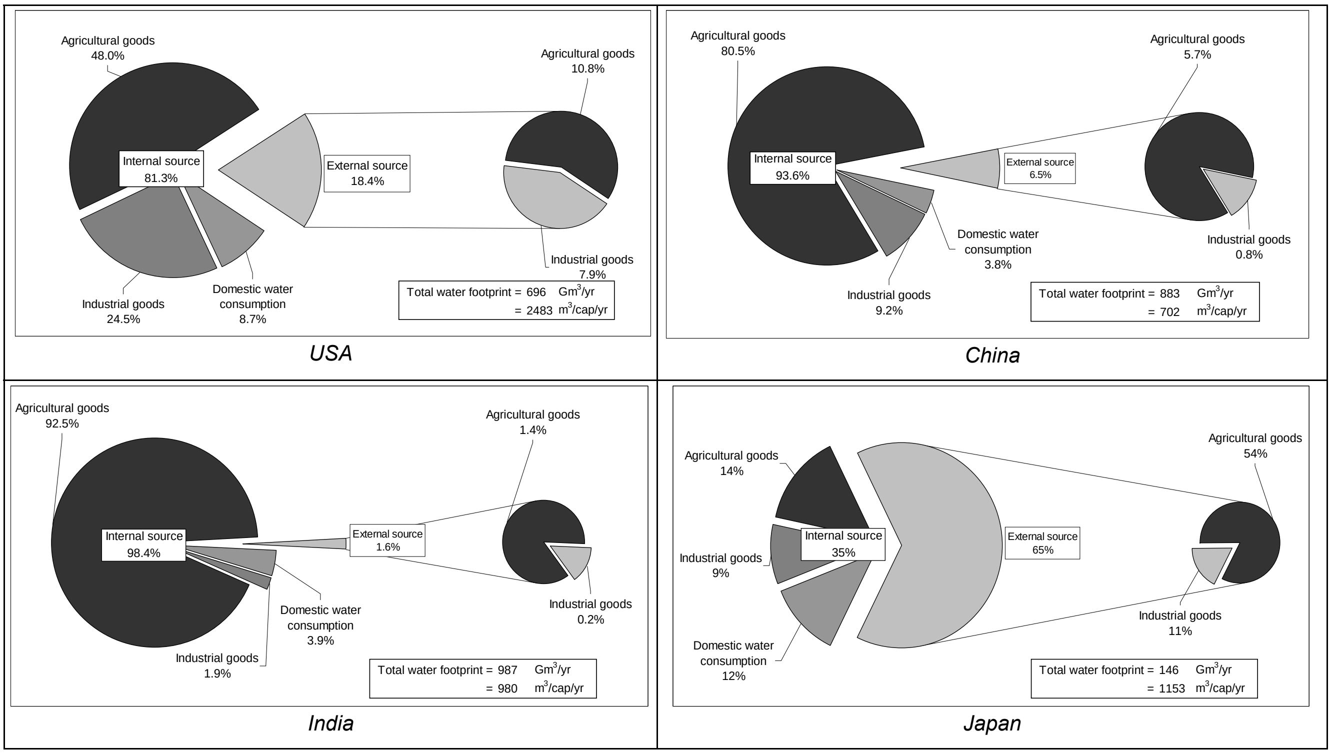


Figure 4.13. Details of the water footprints of the USA, China India and Japan. Period: 1997-2001.

4.5. Correlation between water footprints of nations and a few selected determinants

4.5.1. Water footprints in relation to gross national income

The national water footprints related to domestic water consumption have been plotted against gross national income (GNI) per capita in Figure 4.14. The same has been done for national water footprints due to the consumption of industrial products in Figure 4.15. In both cases we see a positive relation between water footprint per capita and GNI per capita. Note that we have used logarithmic scales in the plots. The effect of GNI on water footprint diminishes at larger GNI per capita. National water footprints related to the consumption of agricultural products have been plotted against GNI per capita in Figure 4.16. We do not see a positive relation as in the previous two figures. The reason is that other factors – climate, agricultural practice and consumption pattern – interfere to such extent that these factors should be filtered out first before we can see the individual effect of GNI per capita. We have not done that in this phase of the study yet.

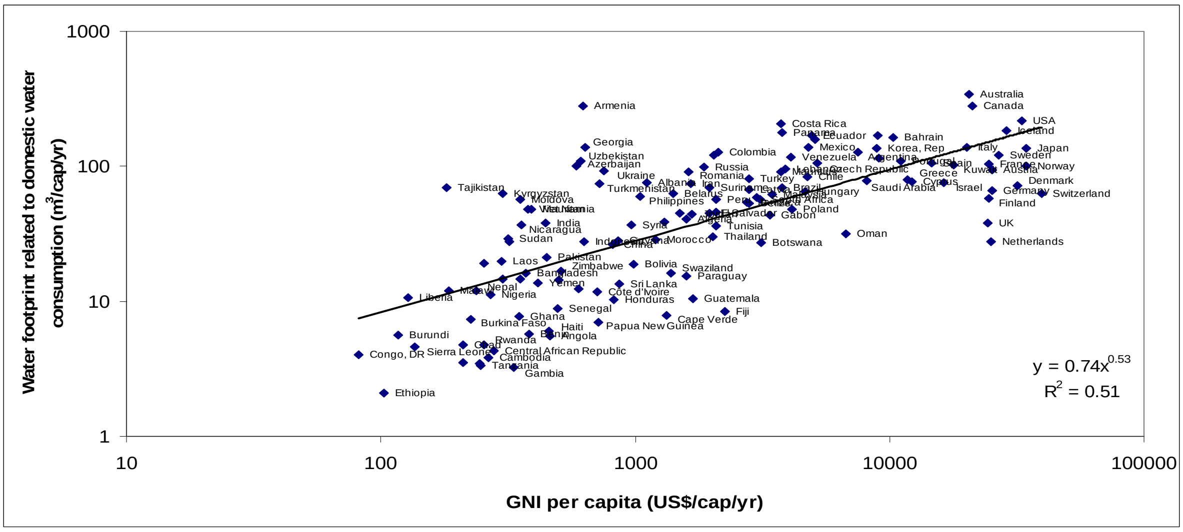


Figure 4.14. Relation between water footprint due to domestic water consumption and gross national income.

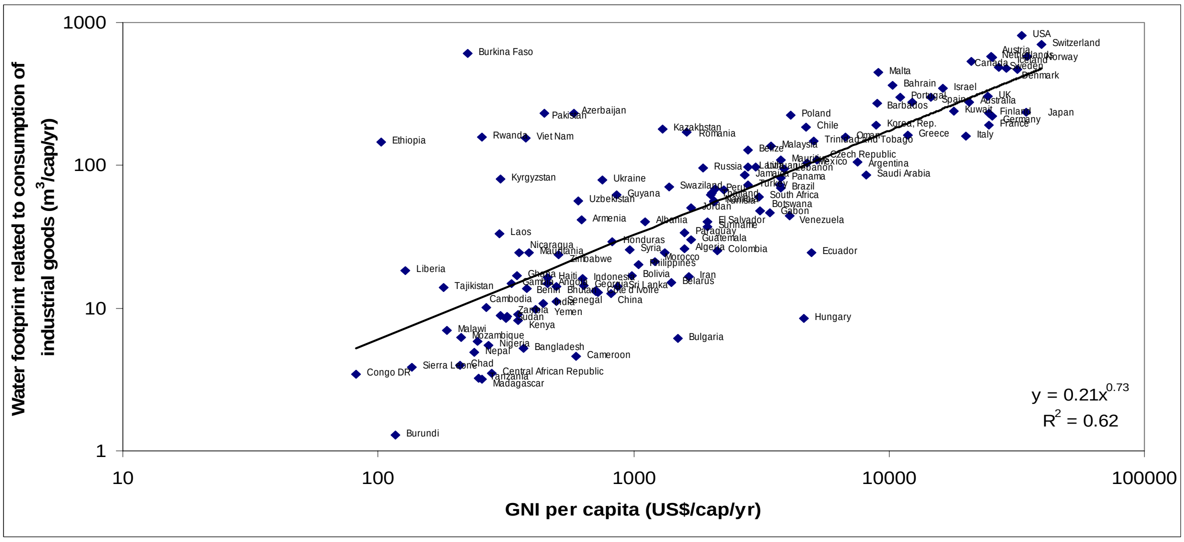


Figure 4.15. Relation between water footprint due to consumption of industrial goods and gross national income.

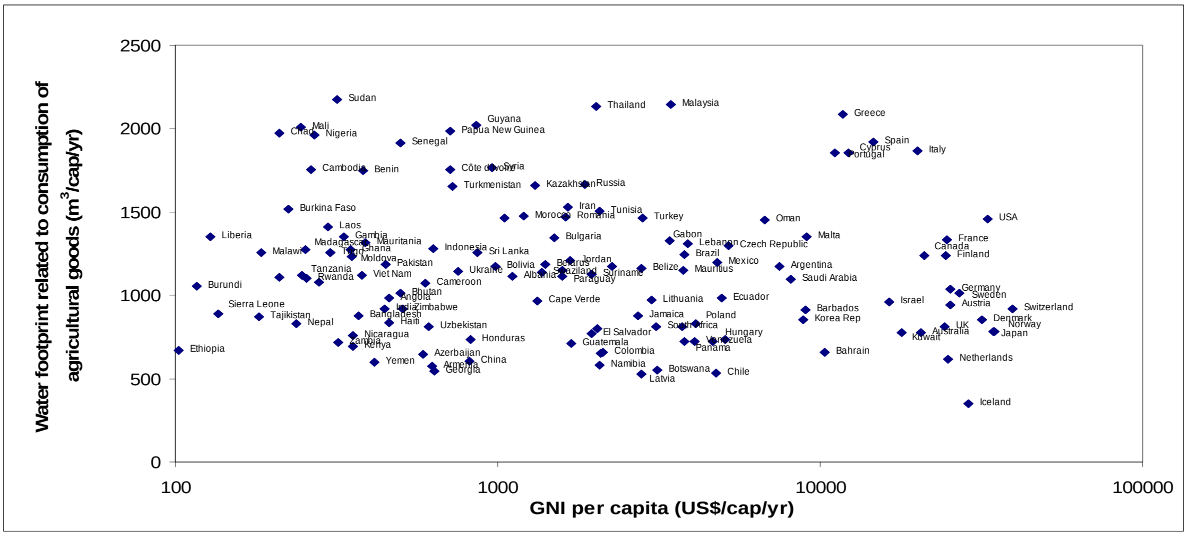


Figure 4.16.Relation between water footprint due to consumption of agricultural products and gross national income.

4.5.2. Water footprints in relation to meat consumption

Average per capita meat consumption data have been taken from the ‘Food Balance Sheets’ of FAO (FAOSTAT, 2004) and plotted against GNI per capita (Figure 4.17). We can see that meat consumption rapidly increases up to a certain level of income (about 5000 US$/yr) and then it becomes less and less sensitive to change in GNI per capita. One would expect a positive relationship between the water footprint due to consumption of agricultural products and meat consumption within the lower income range (<5000 US$/cap/yr), but our data don’t show such a relationship (Figure 4.18). Again, the reason is that there are a number of independent factors determining the water footprint of a nation, so that the individual effect of meat consumption is not apparent at one glance.

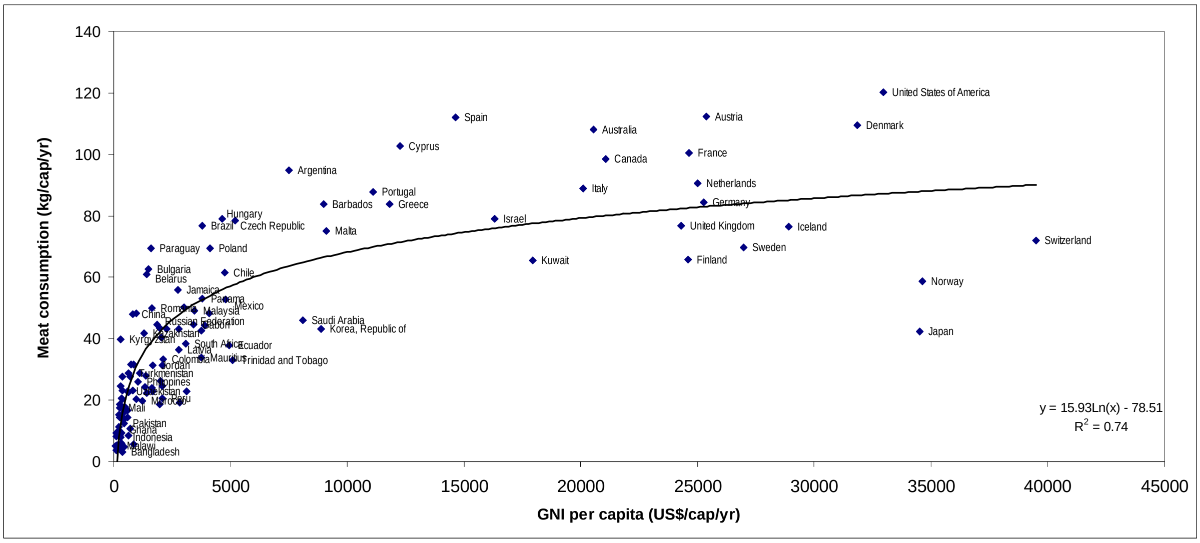


Figure 4.17. Meat consumption in relation to gross national income. Period 1997-2001.

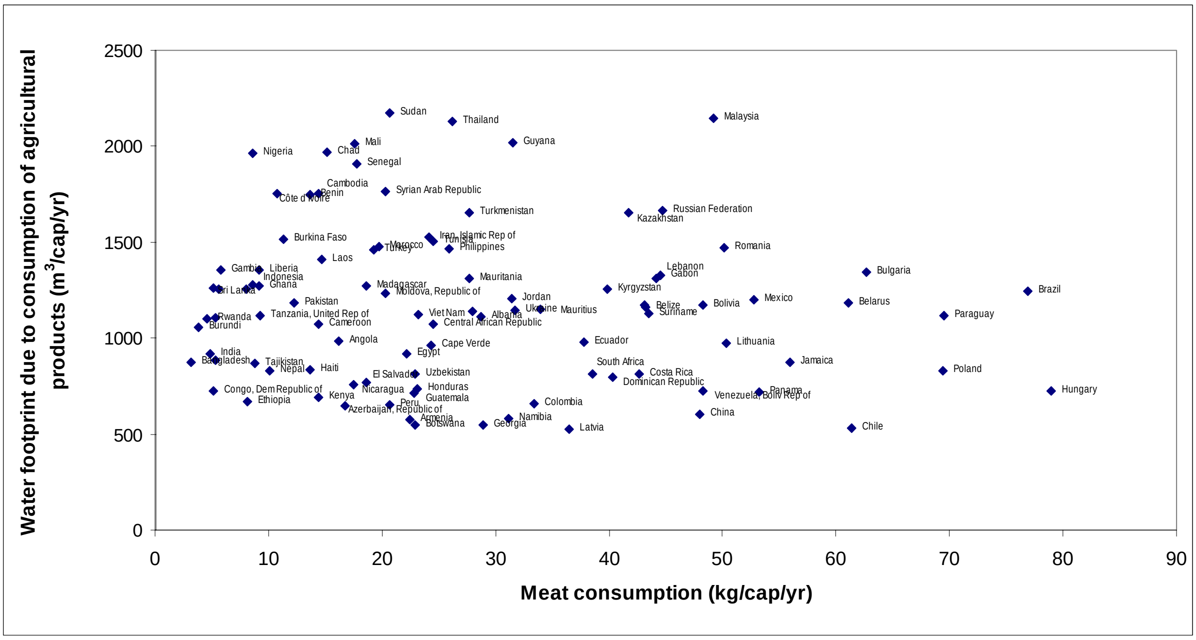


Figure 4.18. Relation between the water footprint due to consumption of agricultural products and meat consumption (only countries with GNI < 5000 US$/cap/yr). Period 1997-2001.

4.5.3. Water footprints in relation to climate

The evaporative demand in a country determines the natural volume of water needed to grow crops. One would expect that warmer countries have a relatively high water footprint related to the consumption of foods produced within the country. Figure 4.19 shows that this is indeed true for nations such as Senegal, Mali, Sudan and Chad. The overall picture however is diffuse, which is caused by the fact that climate is not the sole determinant of the internal water footprint. Countries such as Bahrain, Kuwait and Qatar for instance have a high evaporative demand but a low internal water footprint, because the major share of their agricultural demands are met by import from outside.

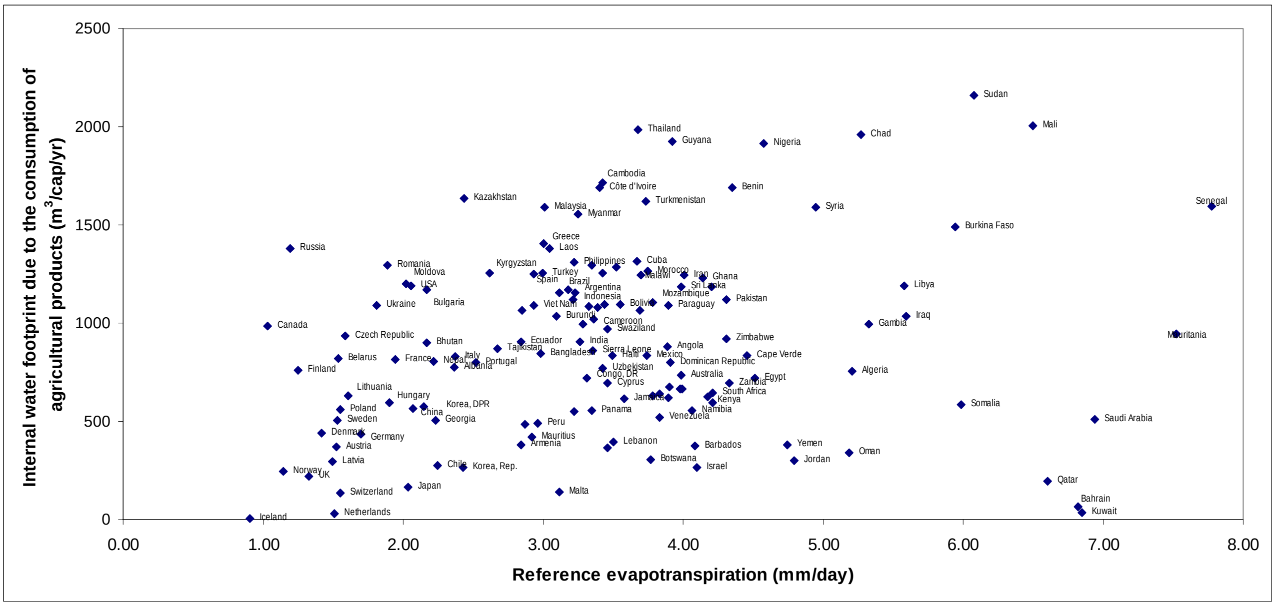


Figure 4.19. Relation between the water footprint due to the consumption of agricultural products and average reference evapotranspiration (average for 12 months from Appendix VI).

4.5.4. Water footprints in relation to the yield of some major crops

The effect of yield on the water footprint insofar related to the consumption of internally produced agriculture products is shown in Figures 4.20 and 4.21 for wheat and rice respectively. As one would expect, some countries with low yields have indeed a high internal water footprint, see for instance Thailand, Sudan, Nigeria and Mali. The picture as a whole however doesn't show a straightforward relation between yield and water footprint, which is understood by the fact that yield is just one determinant, next to climate, food consumption volumes, diet of people and the ratio of import versus domestic production.

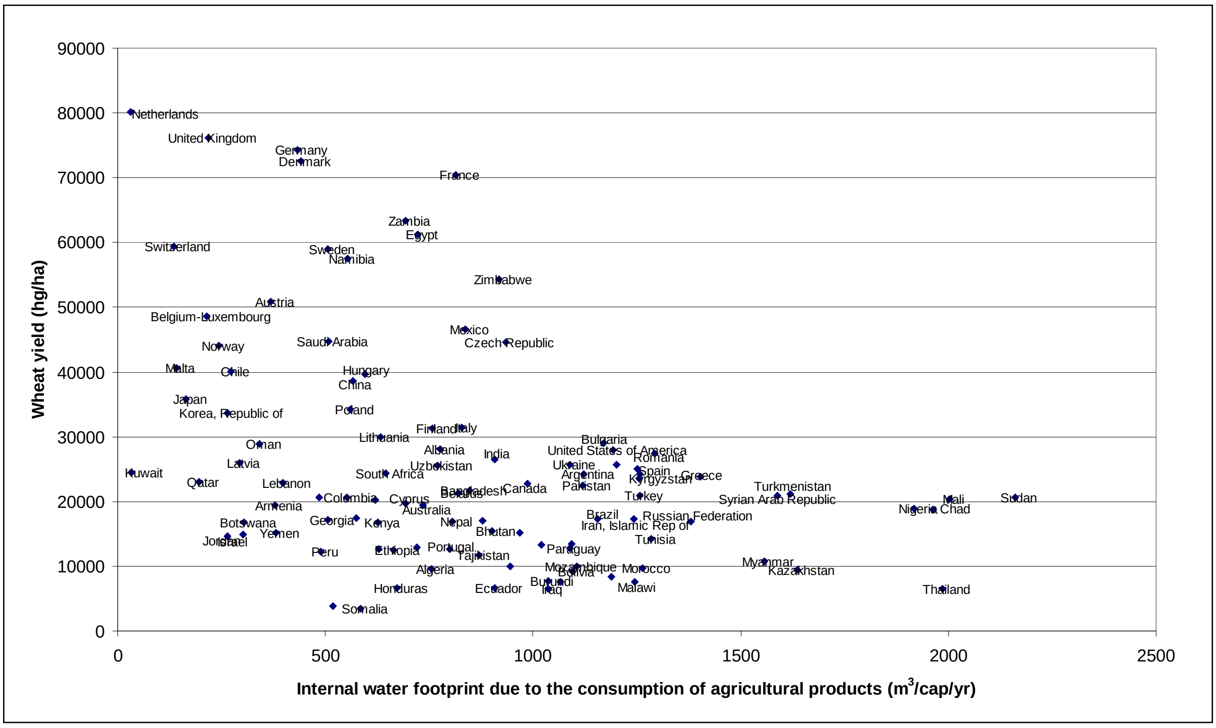


Figure 4.20. The effect of wheat yield on the internal water footprint due to consumption of agricultural products.

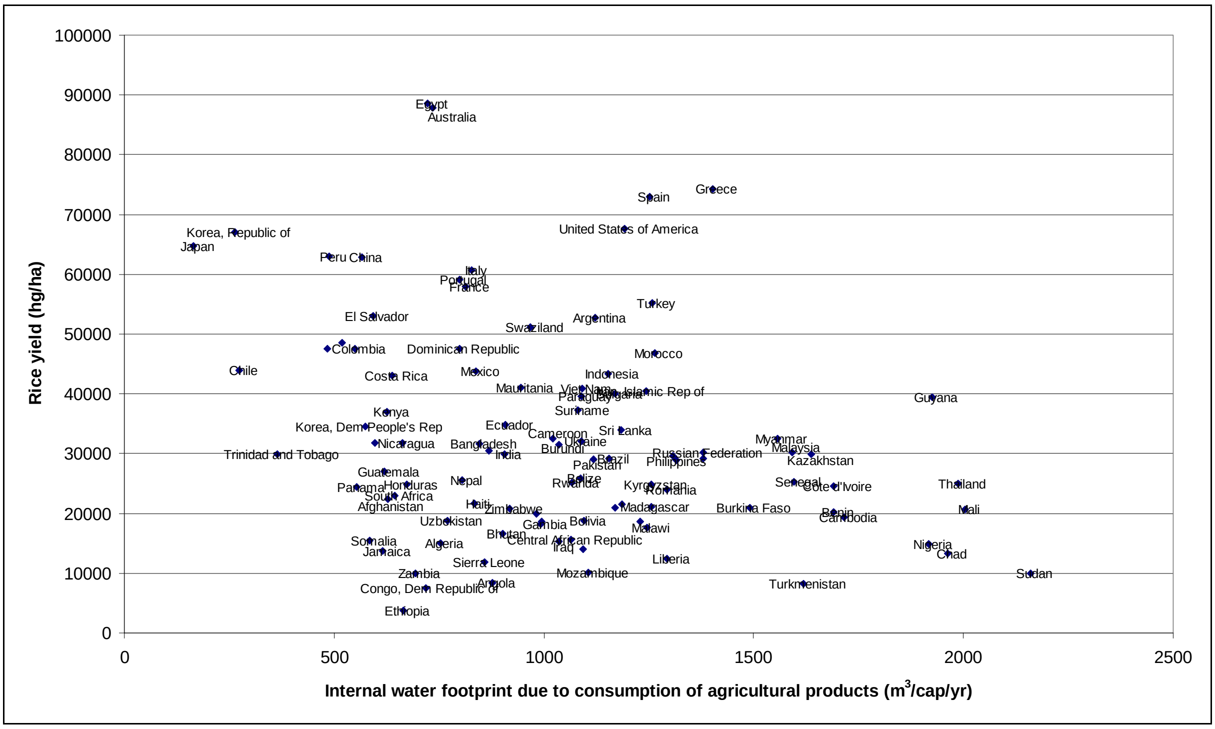


Figure 4.21. The effect of rice yield on the internal water footprint due to consumption of agricultural products.

4.5.5. Water footprints in relation to the average virtual water content of cereals

The relation between the average virtual water content of cereal crops and the water footprint related to the consumption of internally produced agriculture products is presented in Figure 4.22. Generally, the higher the average virtual water content of cereal crops, the higher is the water footprint related to the consumption of internally produced agricultural products. However, Botswana, Somalia and Namibia have a very high average virtual water content of cereals due to the low yields and hot climate but they exhibit a very low internal water footprint related to the consumption of agriculture products. In these countries the per capita consumption of domestically produced goods is very low.

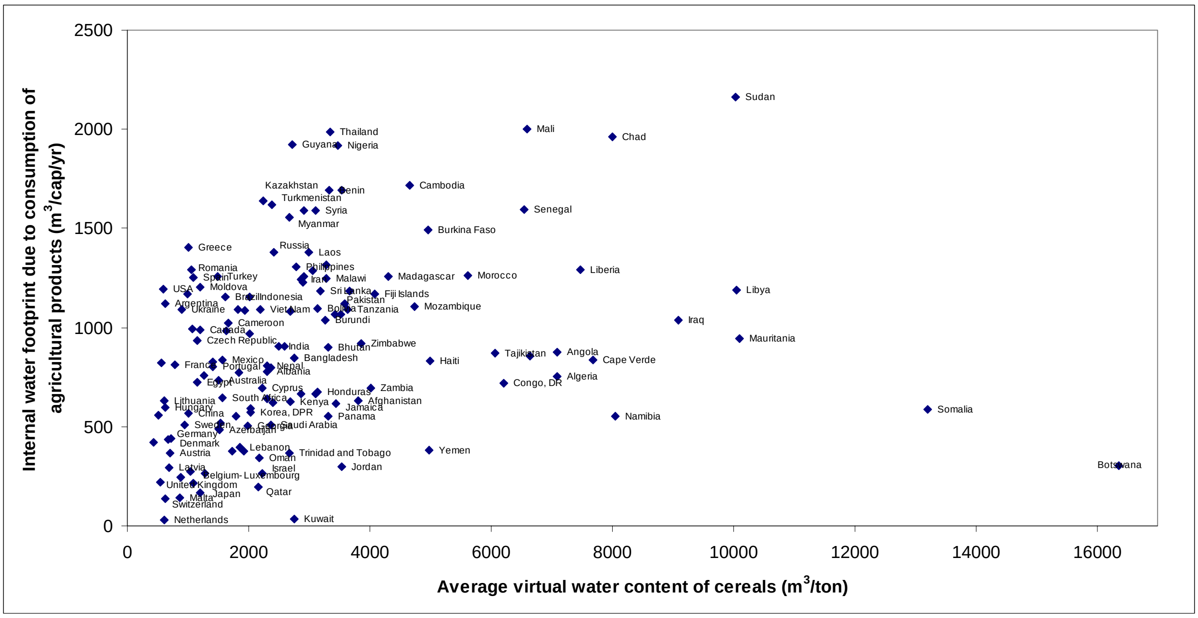


Figure 4.22. Relation between water footprints due to consumption of internally produced agricultural products and the average virtual water content of cereals.

4.6. Dependence on external water resources in relation to national water scarcity

A country faces high water scarcity if the country's water footprint – the total water volume needed to produce the goods and services consumed by the people in the country – is large compared to the volume of renewable water resources available. From a water resources point of view one might expect a positive relationship between water scarcity and water import dependency, particularly in the ranges of high water scarcity. As can be seen in Figure 4.23, there is however not such a clear relationship, although indeed a number of countries – e.g. Kuwait, Qatar, Saudi Arabia, Bahrain, Jordan, Israel, Oman and Lebanon – combine very high water scarcity with very high water import dependency. The water footprints of these countries have largely been externalised.

The reason that the overall picture shown in Figure 4.23 is more diffuse than one would expect from a water resources point of view, is that under current trade regime water is seldom the dominant factor determining international trade of water-intensive commodities. The relative availability of other input factors – notably land and labour – play a role as well, and also existing national policies, export subsidies and international trade barriers.

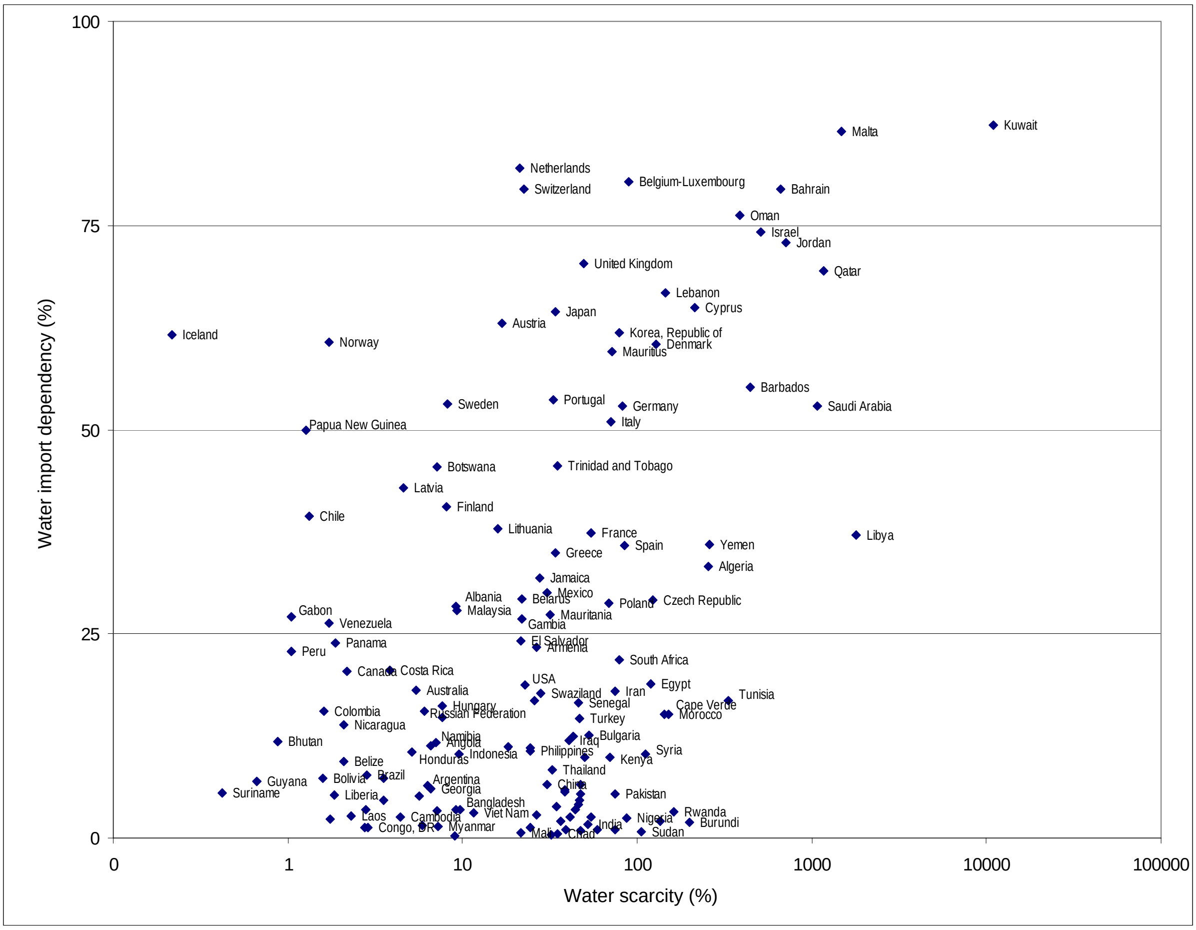


Figure 4.23. Water scarcity versus water import dependency per country.

Various countries have high water scarcity but low water import dependency. There are different explanatory factors. Yemen, known for overdrawing their limited groundwater resources, for instance has a low water import dependency for the simple reason that they do not have the foreign currency to import water-intensive commodities in order to save domestic water resources. Egypt on the other hand combines high water scarcity and low water import dependency intentionally, aiming at consuming the Nile water to achieve food self-sufficiency.

The water scarcity and use of external water resources for some selected countries are presented in Table 4.10. A complete set of data for all countries is included in Appendix XXI.

India is the country with the largest water footprint in the world (987 Gm^3/yr) but it also has a very high national self-sufficiency ratio (98%), which implies that at present India is only little dependent on the import of virtual water from other countries to meet its national demands. The same is true for the people of China, who together have a water footprint of 883 Gm^3/yr and a self-sufficiency ratio of 93%. However, India and China have relatively low per capita water footprints (India 980 m^3/cap/yr and China 702 m^3/cap/yr). If the consumption pattern in these countries changes to that like in the USA or some Western European countries, they will be facing a severe water scarcity in future and probably be unable to sustain their high degree of water self-sufficiency.

Table 4.10. Water scarcity and water import dependency for hundred selected countries. Period: 1997-2001.

Country	Total renewable water resources	Internal water footprint	External water footprint	Total water footprint	Water scarcity	National water self-sufficiency	Water import dependency
	(Gm^3/year)	(Gm^3/year)	(Gm^3/year)	(Gm^3/year)	(%)	(%)	(%)
Afghanistan	65	16.8	0.5	17.3	27	97	3
Algeria	14.4	24.5	12.2	36.7	255	67	33
Angola	184	11.5	1.5	13	7	88	12
Argentina	814	48.3	3.3	51.7	6	94	6
Australia	492	21.8	4.8	26.6	5	82	18
Austria	77.7	4.8	8.2	13	17	37	63
Azerbaijan	30.3	6.5	1.3	7.8	26	83	17
Bahrain	0.1	0.2	0.6	0.8	660	20	80
Bangladesh	1210.6	112.4	4	116.5	10	97	3
Belarus	58	9	3.7	12.7	22	71	29
Belgium-Lux.	21.4	3.8	15.4	19.2	90	20	80
Benin	24.8	10.5	0.4	10.9	44	96	4
Bolivia	622.5	9.2	0.7	9.9	2	93	7
Brazil	8233	215.7	17.9	233.6	3	92	8
Bulgaria	21.3	9.9	1.4	11.3	53	87	13
Burkina Faso	12.5	16.7	0.3	17	136	98	2
Burundi	3.6	7	0.1	7.2	199	98	2
Cambodia	476.1	20.4	0.5	21	4	97	3
Cameroon	285.5	15.3	0.8	16.1	6	95	5
Canada	2902	50	12.8	62.8	2	80	20
Chad	43	14.9	0.1	15	35	99	1
Chile	922	7.3	4.8	12.1	1	61	39
China	2896.6	825.9	57.4	883.4	30	93	7
Colombia	2132	28.8	5.3	34.1	2	84	16
Congo, DR	1283	36.4	0.5	36.9	3	99	1
Côte d'Ivoire	81	27	1.1	28.1	35	96	4
Cuba	38.1	17.2	1.9	19.1	50	90	10
Czech Republic	13.2	11.4	4.7	16.1	123	71	29
Denmark	6	3	4.6	7.7	128	40	60
Dominican Rep.	21	7.7	0.5	8.1	39	94	6
Ecuador	432	14.1	1.1	15.3	4	93	7
Egypt	58.3	56.4	13.1	69.5	119	81	19
Ethiopia	110	42.5	0.4	42.9	39	99	1
Finland	110	5.3	3.6	8.9	8	59	41
France	203.7	69.1	41.1	110.2	54	63	37
Germany	154	59.9	67.1	126.9	82	47	53
Ghana	53.2	23.6	1	24.7	46	96	4
Greece	74.3	16.4	8.8	25.2	34	65	35

	Total renewable water resources	Internal water footprint	External water footprint	Total water footprint	Water scarcity	National water self-sufficiency	Water import dependency
India	1896.7	971.4	16	987.4	52	98	2
Indonesia	2838	242.3	27.7	270	10	90	10
Iran	137.5	84.2	18.4	102.7	75	82	18
Iraq	75.4	27.2	3.7	30.9	41	88	12
Israel	1.7	2.2	6.4	8.6	514	26	74
Italy	191.3	65.9	68.7	134.6	70	49	51
Japan	430	51.9	94.2	146.1	34	36	64
Jordan	0.9	1.7	4.6	6.3	713	27	73
Kazakhstan	109.6	26.6	0.4	27	25	99	1
Kenya	30.2	19.1	2.1	21.2	70	90	10
Korea Rep.	69.7	21	34.2	55.2	79	38	62
Korea, DPR	77.1	16.7	2.1	18.8	24	89	11
Kuwait	0	0.3	1.9	2.2	10895	13	87
Kyrgyzstan	20.6	6.6	0	6.6	32	100	0
Lebanon	4.4	2.1	4.3	6.4	146	33	67
Libya	0.6	6.8	4	10.8	1793	63	37
Madagascar	337	19.5	0.3	19.8	6	98	2
Malawi	17.3	12.9	0.1	13	75	99	1
Malaysia	580	38.9	15	53.9	9	72	28
Mali	100	21.5	0.1	21.6	22	99	1
Malta	0.1	0.1	0.6	0.7	1478	13	87
Mexico	457.2	98	42.1	140.2	31	70	30
Morocco	29	37	6.6	43.6	150	85	15
Mozambique	216.1	19.4	0.1	19.5	9	100	0
Myanmar	1045.6	74.4	1.1	75.5	7	99	1
Nepal	210.2	18.7	0.7	19.3	9	96	4
Netherlands	91	3.5	15.9	19.4	21	18	82
Nigeria	286.2	242.2	5.9	248.1	87	98	2
Oman	1	0.9	2.9	3.8	389	24	76
Pakistan	222.7	157.3	8.9	166.2	75	95	5
Papua New Guinea	801	5.1	5.1	10.2	1	50	50
Paraguay	336	5.8	0.1	5.9	2	98	2
Peru	1913	15.4	4.6	20	1	77	23
Philippines	479	104.4	12.5	116.8	24	89	11
Poland	61.6	30.4	12.3	42.6	69	71	29
Portugal	68.7	10.5	12.1	22.6	33	46	54
Qatar	0.1	0.2	0.4	0.6	1176	31	69
Romania	211.9	34.6	4.3	38.9	18	89	11
Russia	4507.3	228.9	42.1	271	6	84	16
Rwanda	5.2	8.2	0.3	8.4	162	97	3

	Total renewable water resources	Internal water footprint	External water footprint	Total water footprint	Water scarcity	National water self-sufficiency	Water import dependency
Saudi Arabia	2.4	12.2	13.7	25.9	1079	47	53
Senegal	39.4	15.1	3	18.2	46	83	17
South Africa	50	30.9	8.6	39.5	79	78	22
Spain	111.5	60.4	33.6	94	84	64	36
Sri Lanka	50	22.1	1.6	23.7	47	93	7
Sudan	64.5	67.7	0.6	68.3	106	99	1
Sweden	174	6.7	7.6	14.4	8	47	53
Switzerland	53.5	2.5	9.6	12.1	23	21	79
Syria	26.3	26.2	3	29.2	111	90	10
Tanzania	91	36.5	1	37.5	41	97	3
Thailand	409.9	123.2	11.2	134.5	33	92	8
Tunisia	4.6	12.6	2.6	15.2	333	83	17
Turkey	229.3	92.2	15.8	107.9	47	85	15
Turkmenistan	24.7	8.8	0.2	9	36	98	2
Ukraine	139.6	62.4	3	65.4	47	95	5
United Kingdom	147	21.7	51.4	73.1	50	30	70
USA	3069.4	565.8	130.2	696	23	81	19
Uzbekistan	50.4	22.8	1.3	24	48	95	5
Venezuela	1233.2	15.6	5.6	21.1	2	74	26
Viet Nam	891.2	100.2	3.1	103.3	12	97	3
Yemen	4.1	6.9	3.8	10.7	261	64	36
Zimbabwe	20	11.8	0.1	11.9	59	99	1

5. Conclusion

The global water footprint is 7450 Gm^3/yr, which is 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 factors explaining high water footprints. A first factor is the total volume of 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. 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).

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.

Virtual water can be regarded as an alternative source of water. Virtual water import can be used by national governments as a tool to release the pressure on their domestic water resources. Jordan for instance annually imports a virtual water volume that is more than five times its own annually renewable water resources. Although saving their own domestic water resources, it increases Jordan's dependency on other nations. Other water-scarce countries such as Israel, Lebanon, Kuwait, Qatar, Bahrain, Oman and Malta have a similar high water import dependency.

Global virtual water trade can effectively save water if products are traded from countries with high to countries with low water productivity. For example, Mexico imports wheat, maize and sorghum from the USA (equivalent to 7.1 Gm^3/yr). If Mexico would produce the imported crops domestically, it would require 15.6 Gm^3 of water per year. Thus, from a global perspective, the trade of cereals from the USA to Mexico saves 8.5 Gm^3/yr.

The current assessment of water footprints of nations carries a number of shortcomings, even though a number of improvements have been carried through if compared to our earlier assessments (Hoekstra and Hung, 2002; Chapagain and Hoekstra, 2003a). An important shortcoming is that the estimates of virtual water content of crops are based on crop water requirements, which leads to overestimates in those cases where actual water availability is lower than the crop water requirement. The calculations could be improved by using the actual water use by crops as a basis, which however will require more specific data per crop per country (that we did not have for the current study).

A matter for future consideration is the issue of including or excluding irrigation losses from the water footprint definition. In the current study we have not included them mainly for the practical reason that data on irrigation losses are generally not specified per crop, so that they cannot be included in the calculation of the virtual water content of specific crops. But it can be argued that it is indeed right to exclude irrigation losses, because these losses largely return to the system again. The counter-arguments in favour of including the losses are that the withdrawal in itself has an impact already that should not be neglected (the return flows do not return to the precise place where to were withdrawn), that a fraction of the total loss really gets lost for further use through evaporation, and that return flows are often polluted and cannot be reused without treatment or dilution.

A second shortcoming in the current assessment of water footprints is that we have focused on expressing the impact of human activities on the *quantitative* use of water resources. The water footprint concept has been defined in this study as the quantity of water required to fulfil human's demand for goods and services. Further development of the water footprint concept would expand the water footprint definition in order to include impacts of human activities on water quality as well.

Besides improvements, there is also room for refinements. The water footprint related to the consumption of industrial products has been estimated for instance in a relatively quick and crude way, without specifically looking at the specific water requirements for all kind of different industrial products. The methodology currently applied yields results that suffice as overall estimates, but gives little product-specific information.

Finally, the challenge is to start using the water footprint concept as a practical tool to analyse how consumption patterns affect water use, how future changes in consumption patterns are likely to impact on water, how countries can externalise their water footprint in order to reduce the pressure on the domestic water resources and how other countries can profit from their relative abundance of water by exporting water-rich commodities.

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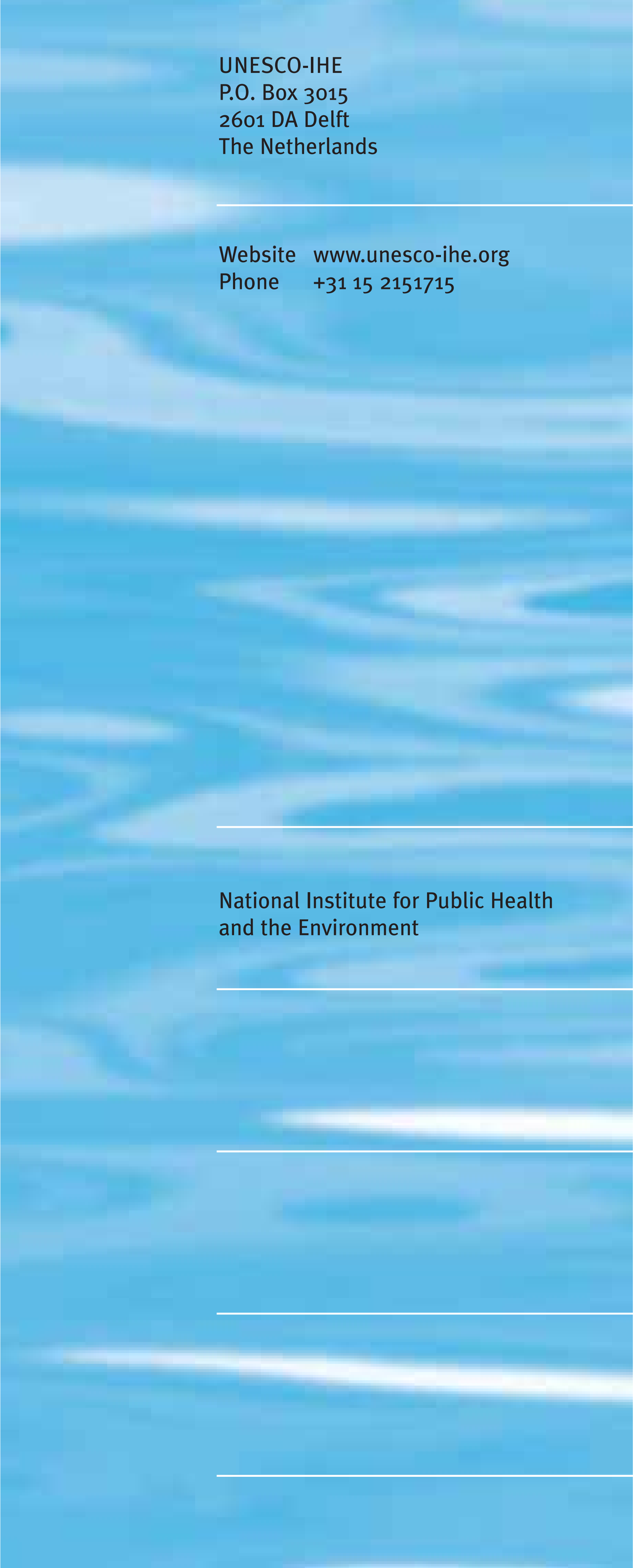

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