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G.P. Zhang
A.Y. Hoekstra
D. Tickner

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"SOLVING THE WATER CRISIS: COMMON ACTION TOWARD A SUSTAINABLE WATER FOOTPRINT"

PLANET UNDER PRESSURE CONFERENCE, LONDON, 26 MARCH 2012

G.P. ZHANG [1]

A.Y. HOEKSTRA [1, 2]

D. TICKNER [3]

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[1] Water Footprint Network, The Netherlands
[2] University of Twente, Enschede, The Netherlands
[3] WWF – UK, United Kingdom

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Preface

The Earth system has experienced significant changes due to impacts of human activity. We face the challenge of improving the livelihoods of people while sustaining the health of the planet. The global scientific community must deliver to society the knowledge necessary to assess the risks humanity is facing from global change. It must provide knowledge of how society can effectively mitigate dangerous changes and cope with changes we cannot manage. As a lead up to the United Nations Conference on Sustainable Development (the Rio+20 Earth Summit) in Rio de Janeiro, Brazil, 20-22 June 2012, the global scientific community gathered in the Planet under Pressure (PuP) conference in London, 26-29 March 2012 (www.planetunderpressure2012.net). The conference discussed solutions, at all scales, to move societies on to a sustainable pathway. The Planet under Pressure conference brought together three thousand delegates at the conference venue. Over 3,500 attended virtually via live webstreaming. The conference focused the scientific community's and the wider world's attention on climate, ecological degradation, human well-being, planetary thresholds, food security, energy, governance across scales and poverty alleviation. The conference discussed solutions, at all scales, to move societies on to a sustainable pathway.

Part of the Planet under Pressure conference was a seminar session on the first day of the conference called "Solving the Water Crisis: Common Action toward a Sustainable Water Footprint". The aim of the seminar was to better understand the water footprint of human activities and discuss strategies to move towards a sustainable, efficient and equitable use of freshwater resources.

This volume of proceedings is a collection of papers that were discussed at the seminar and peer-reviewed and revised afterwards. The papers present research and applications of Water Footprint Assessment (WFA) at the level of different entities – nations, river basins and business – and discuss the pressure of water consumption and pollution on the water system from different perspectives: production, consumption and international trade. In the first paper, **Zoumides** and his co-authors estimate the water footprint of crop growing on Cyprus, using a local spatiotemporal model, and show that the local model is able to capture the inter-annual effects of climate variability, which is thus potentially more useful to guide policy decisions then previously employed global models. **Zhang** *et al*., in the second paper, provide insight into the impacts of China's international trade on the nation's water resources, using an input-output-based virtual water analysis with a sectoral-regional lens. In the third paper, **De Miguel** *et al*. use a spatially distributed water balance model to compute the water consumption (blue and green water footprint) of the agricultural sector in the Duero River Basin in Spain. The fourth paper, authored by **Vanham,** analyses the water footprint of Austria from the consumption perspective, assesses the effect of diet composition on the water footprint of national consumption, and indicates that moving to a more healthy diet would reduce the water footprint. Lastly, **Francke** and **Castro** map the business water footprint of Natura, a Brazilian cosmetic company, based on the whole product life cycle, which includes the use and disposal phase, aiming to understand the impacts of the company's water footprint in order to support decisions driving towards sustainability.

The discussion during this seminar showed that the pressure of human production and consumption on the Earth water system and the associated impacts have been mounting. The work presented in this proceedings demonstrates that the water footprint is a unique and powerful instrument to help measure the state of the pressure, and that Water Footprint Assessment provides a unified framework for water footprint accounting, and can aid sustainability assessment and response formulation with the ultimate aim to move towards better water governance and stewardship. Yet, in the meantime, it is obvious that we are only at the very beginning of a collective undertaking of the global community to form and consolidate a unified front to solve the water crisis.

We would like to thank all the participants of the seminar and the authors of these proceedings for their collaborative support and valuable contribution.

Dr. **Guoping Zhang**, Water Footprint Network, Enschede, The Netherlands
Prof. Dr. Ir. **Arjen Y. Hoekstra**, University of Twente, Enschede, The Netherlands
Dr. **Dave Tickner**, WWF-UK, London, United Kingdom

1. Global versus local crop water footprints: the case of Cyprus

C. Zoumides[1], A. Bruggeman[2], T. Zachariadis[1]

[1] Cyprus University of Technology, Department of Environmental Science and Technology, Limassol, Cyprus

[2] The Cyprus Institute, Energy, Environment and Water Research Center, Nicosia, Cyprus

Abstract

The formulation of appropriate policies towards improving water resource management requires prompt and accurate information on water use. Soil water balance models provide the means to estimate agricultural water use, in the absence of metered data. This paper presents the spatiotemporal model that was used to assess the blue and green water footprint of crop production in Cyprus, for the period 1995-2009. Furthermore, the paper quantifies the difference between the results of this study with the estimates from the advanced global water use assessments of Siebert and Döll (2010) and Mekonnen and Hoekstra (2011) for Cyprus. The results of the local model show that, on average, total agricultural water use in Cyprus was 506 Mm^3/year, of which 63% is attributed to green water and 37% to blue water. Blue water use ranged from 160 Mm^3/year to 214 Mm^3/year, while green water ranged from 169 Mm^3/year to 441 Mm^3/year. The global versus local comparison revealed that the Siebert and Döll (2010) estimates for Cyprus were 72% lower for total green water use and 41% higher for blue water use, for the period 1998-2002. In the case of the Mekonnen and Hoekstra (2011) estimates, the total green water use was identical with the result of the local model, while blue water use was 43% higher in the global model, for the period 1996-2005. The discrepancies between the results of global and local models are attributed to the different input data, modelling assumptions and parameters adopted by each model. From a policy perspective, global models are not particularly useful as they provide average or static results with high uncertainty level related to data limitations. On the other hand, the local model captured the inter-annual effects of climate variability on crop water use and the results provided can potentially guide policy decisions to a sustainable green-blue water use strategy.

Introduction

In the light of globalisation, population growth and climate change, water resources management is increasingly becoming a major sustainability challenge, especially for arid and semi-arid regions. It is widely acknowledged that water scarcity or insecurity is not only subject to physical factors and constraints, but also due to poor management of available water resources (Molden et al., 2007). The formulation of appropriate policies towards improving water resources management requires prompt and accurate information on when, where and for which sector water is used (EEA, 2012). Unlike water use in the domestic and industrial sectors, there is significant lack of information in most countries regarding agricultural water use, as irrigation abstractions from rivers, dams and aquifers (i.e. blue water), are rarely fully metered and charged (Easter and Liu, 2005). Furthermore, the contribution of the "non-usable" part of the water balance is often neglected by water managers when analysing agricultural water use (Falkenmark, 2003). This so-called green water refers to the precipitation that fills up the soils, evaporates or transpires through vegetation and satisfies all or part of crop water requirements. Recent studies emphasise the strategic importance of green water in ensuring food and water security as well as sustaining natural ecosystems (Falkenmark and Rockström, 2004; Falkenmark et al., 2009; Aldaya et al., 2010).

In the array of available water management tools and metrics, the 'water footprint' provides a holistic framework for quantifying and analysing the human appropriation of freshwater resources, by linking production systems with trade and consumption patterns (Hoekstra et al. 2011). The water footprint, introduced by Hoekstra (2003) and further elaborated by Hoekstra and Chapagain (2008), builds upon the concept of 'virtual water'. This term has been used by Allan (1993, 1998) to describe the flow of water embedded in traded crop products, which can potentially alleviate water insecurity in arid and semi-arid regions. The quantification of virtual water trade flows requires climate-specific estimation of crop water use. In the case of crop production, the water footprint (or virtual water content) measures the total cumulative volume of green and blue water use per unit of crop output; some studies also include the grey water, which refers to the theoretical volume of water required to dilute the pollution load resulting from the use of agrochemicals (Mekonnen and Hoekstra, 2011). Methodologically, the quantification of crop water footprints is based on soil water balance models, which interpolate climatic, crop and soil parameters to determine crop water requirements. These models have been developed over the past 30 years to enhance agricultural water management (Bastiaanssen et al., 2007) and have been applied extensively at different spatiotemporal scales.

During the last 15 years there has been an increasing interest in large-scale consumptive water use modelling, particularly at the global level. Early global assessments were based on broad assumptions that treated countries or continents as a whole. Postel et al. (1996) for instance, estimated the human appropriation of renewable water resources using global average evapotranspiration and net primary production in human-dominated ecosystems. Seckler et al. (1998) applied a water balance model to quantify and project the world's blue water demand and supply for the period 1990-2025. Rockström et al. (1999) were the first to explicitly assess the global green water flows for different climatic zones and biomes, including cropland. Chapagain and Hoekstra (2004) made a first quantification of virtual water trade flows and estimated the water footprint of nations for the period 1997-2001, using long-term monthly average climatic variables per country.

More recently, researchers attempted to enhance the precision of estimates, by improving the model input parameters. For example, Wriedt et al. (2009) estimated blue water requirements in Europe under different irrigation strategies, by combining regional data on crop distribution and irrigated areas, with spatial data on soils and climate. Liu and Yang (2010) assessed the global green and blue consumptive water use in 22 cropland categories around the year 2000, at 30 arc-minutes spatial resolution. Their results showed that global crop water use was 5938×10^9 m^3/year, of which the green water contribution was 84%. Siebert and Döll (2010) performed a similar assessment using 26 crop classes at a spatial resolution of 5 arc-minutes, and found that total crop water use at a global level was 6685×10^9 m^3/year, of which 5505×10^9 m^3/year was green water, and 1180×10^9 m^3/year was blue water. Their study covered the period 1998-2002 and was undertaken using a global monthly grid-based dataset for irrigated and rain-fed crop areas (MIRCA2000), and daily climatic variables disaggregated from long-term monthly values. In a similar fashion, Mekonnen and Hoekstra (2011) applied a global daily soil water balance model to estimate the average green, blue and grey water footprint of 146 primary crops at 5 arc-minutes resolution, for the period 1996-2005. They found that, on average, the global crop production water footprint use was 7404×10^9 m^3/year; 78% green, 12% blue and 10% grey water footprint.

Despite the significant improvements in global models, the results of the abovementioned studies are subject to limitations and uncertainties, associated with the quality of input data and modelling assumptions. Furthermore, global water use assessments provide static or average results, which mask the temporal effects of climate variability on area and water use. This paper presents the spatiotemporal model that was used to compute the consumptive blue and green water use and the water footprint of crop production in Cyprus, for the period 1995-2009. The model utilised daily climatic variables, year-to-year land use data at community level, and local knowledge regarding crop management practices. The objective of the current study was to quantify the difference between the results of the local model, and the estimates from the global assessments of Siebert and Döll (2010) and Mekonnen and Hoekstra (2011) for Cyprus. Furthermore, the paper examines the reasoning for the difference between the outputs of global and local models, by providing a brief discussion regarding the limitations associated with the input parameters employed within each model, and concludes by assessing the usability of global and local models from a policy point of view.

Methodology and Data

Background

Cyprus is an island-state, located in the eastern corner of the Mediterranean Sea. This study deals with the southern two-third of the island, covering an area of 5760 km^2, which is governed by the Republic of Cyprus. Topographically, the island is dominated by two mountain ranges, Troodos in the central-west and Kyrenia range in the north. Agriculture is concentrated in the plain between the two mountain ranges and in the narrow alluvial plains along the coast (Figure 1). Cyprus has a semi-arid climate associated with limited water resources. The mean annual precipitation varies from 300 mm in the central plain to 1,100 mm on the top of Troodos mountains, with most rainfall occurring during winter months. Droughts occur regularly as a result of large inter-annual variation in precipitation, which have been intensified over the last four decades. Records indicate that the mean annual precipitation has decreased from 541 mm during the period 1901–1970 to 466 mm in the period 1971–2010 (CMS, 2012). It is expected that in the near future droughts will become even worse as a result of climate change (Hadjinicolaou et al., 2011).

The model developed by Bruggeman et al. (2011), was used to compute daily soil water balances and water uses of 83 crops grown in 431 communities in Cyprus, for the period 1995-2009. The model follows the FAO-56 dual crop coefficient approach for computing crop evapotranspiration (ET_c) and scheduling irrigation (Allen et al., 1998). Computations start after the dry summer months on 1st of September, which is the beginning of the hydro-meteorological year. The model uses one spin-up year to provide expected initial values for the soil moisture. The procedure followed as well as the modelling input data are described below.

Methodology

The computation of crop evapotranspiration is a two-step process. First, the reference evapotranspiration (ET_0) is computed from the daily climate parameters and the reference surface characteristics. Secondly, the crop evapotranspiration (ET_c) of each crop is computed from ET_0 using crop-specific coefficients for each crop development stage. For the reference surface, Allen et al. (1998) selected a hypothetical grass crop with a height of 0.12 m, a surface resistance of 70 s/m and an albedo of 0.23. The resulting FAO Penman-Monteith equation is given as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_0 is the reference evapotranspiration (mm/day), Δ is the slope of the vapour pressure curve (kPa/^{o}C), R_n is the net radiation at the crop surface (MJ/m^2 per day), G is the soil heat flux density (MJ/m^2 per day), T is the daily mean air temperature (^{o}C), u_2 is the wind speed at 2 m height (m/s), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa) and γ is the psychometric constant (kPa/^{o}C).

For the second step, following the dual crop coefficient approach, the crop evapotranspiration was computed as:

$$ET_c = (K_{cb} + K_e)ET_0 \tag{2}$$

$$ET_a = (K_s K_{cb} + K_e)ET_0 \tag{3}$$

$$K_e = K_r(K_{c\max} - K_{cb}) \leq f_{ew} K_{c\max} \tag{4}$$

where ET_c is the crop evapotranspiration with no limits on water availability (mm/day), K_{cb} is the basal crop coefficient, K_e is the soil evaporation coefficient, ET_0 is the reference evapotranspiration (mm/day), ET_a is the actual plant water use (mm/day), K_s is a stress coefficient (0-1), K_r is an evaporation reduction coefficient (0-1), $K_{c\ max}$ is the maximum possible evapotranspiration (1.05-1.3) and f_{ew} is the fraction of the soil that is both exposed to radiation and wetted.

The crop coefficient K_{cb} is a function of crop growth stage. The growing period is divided into four distinct stages: initial (l_{ini}), crop development (l_{dev}), mid-season (l_{mid}) and late season (l_{late}). The model uses three crop coefficients ($K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$) to represent the average values for K_{cb} during the initial, mid-season and maturity; the K_{cb} values for the development and the late season period are linearly interpolated.

Crop coefficients for the mid and late stages were adjusted for climate effects, according to:

$$K_{cb} = K_{cb(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{5}$$

$K_{cb\ (Tab)}$ is the $K_{cb\ mid}$ or $K_{cb\ late}$ stages if ≥ 0.45, RH_{min} is the daily minimum relative humidity (%), h is the mean crop height (m), and all other parameters are as previously defined.

For irrigated crop areas, irrigation is applied when soil water in the root zone falls below the readily available water level. Considering the general limited soil depths in Cyprus, the model did not compute the crop root zone development, but used the full root zone and a maximum irrigation depth of 50 mm, based on local irrigation practices. For rain-fed crops, when the soil water content falls below readily available water, the stress coefficient (K_s, equation 3) decreases linearly towards its minimum value of 0.0 at wilting point.

Similarly to the stress coefficient, the soil evaporation reduction coefficient (K_r) is at its maximum value of 1.0 until the readily evaporable soil water has evaporated, and then decreases linearly to 0.0 as evaporation approaches the soil's total evaporable water. The fraction of the soil that is wetted is set based on the irrigation method used (i.e. drip systems, micro and low-pressure sprinklers). Thus, field irrigation application efficiencies (evaporation losses) were computed by the model.

The blue crop water use (CWU_{blue}, m^3) is the total irrigation water applied to the crops during the season. The green water in irrigated crops ($CWU_{greenIR}$, m^3) is the total seasonal ET_a, minus the applied irrigation. For rain-fed crops, blue crop water use is 0 and green crop water use ($CWU_{greenRF}$, m^3) is the total seasonal ET_a.

Yield reduction fractions for rain-fed crops were computed using the equations of Allen et al. (1998):

$$\frac{Y_a}{Y_m} = 1 - K_y\left(1 - \frac{ET_a}{ET_c}\right) \tag{6}$$

where Y_a is the actual yield (ton/ha), Y_m is the maximum attainable yield under no stress conditions (ton/ha), K_y is a yield response factor, ET_a is the actual seasonal crop evapotranspiration (mm) and ET_c is the seasonal crop evapotranspiration in the absence of water stress (mm).

For crops that are grown both under irrigated and rain-fed conditions (e.g., wheat, olives), it was assumed that the irrigated crop area would achieve an optimal yield (Y_m). Thus, within any given year, the average irrigated and rain-fed yields of a selected crop were computed as:

$$Y_{IR} = \frac{Prod_{TOT}}{\left(A_{IR} + \frac{Y_a}{Y_m} \times A_{RF}\right)} \tag{7}$$

$$Y_{RF} = \frac{Y_a}{Y_m} \times Y_{IR} \tag{8}$$

where Y_{IR} is the yield of a specific crop under irrigated conditions (ton/ha), Y_{RF} is the yield of the crop under rain-fed conditions (ton/ha), $Prod_{TOT}$ is the total production of the selected crop (ton), A_{RF} and A_{IR}, refer to the rain-fed and irrigated area of the selected crop (ha), and Y_a/Y_m is the yield reduction fraction computed by the model

The blue and green water footprints of irrigated crops were computed by dividing CWU_{blue} and $CWU_{greenIR}$ (m^3) with crop production under irrigated areas ($Prod_{IR}$, tons). The green water footprint for rain-fed crops was calculated by dividing $CWU_{greenRF}$ (m^3) with the crop production under rain-fed areas ($Prod_{RF}$, tons). The national weighted average crop water footprint (i.e. in both irrigated and rain-fed crop areas) was calculated by dividing blue (CWU_{blue}) and total green crop water use ($CWU_{greenIR+RF}$) with total production ($Prod_{TOT}$).

Data

Daily data from 70 precipitation gauges and 34 climate stations, for the period January 1995 to December 2009, were obtained from the Cyprus Meteorological Service. The location of the climate stations is presented in Figure 1. The climate parameters of each station were graphed and compared with neighbouring stations to check for errors and assess data quality. The climate stations were allocated to each of the 431 Cypriot communities in the study, based on the distance and elevation difference between the climate station and the centre point of the agricultural plots in each community.

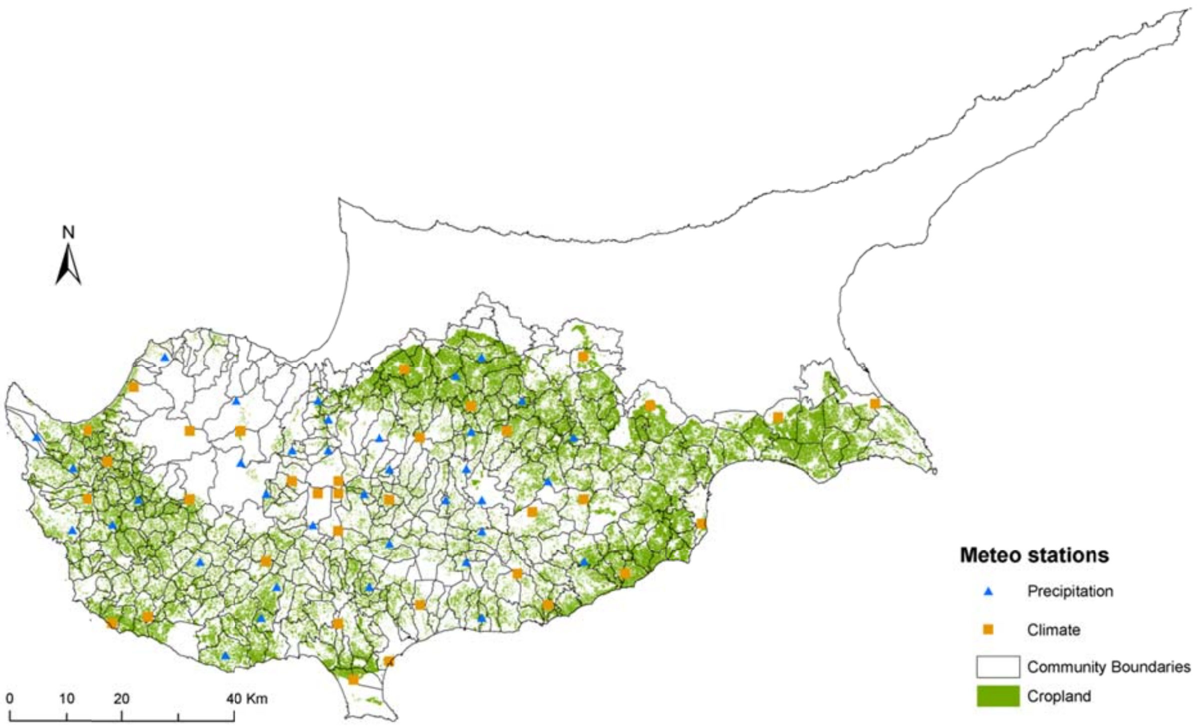

Figure 1. Location of the climate stations and precipitation gauges used in this study. The map also indicates the cropland within the 431 communities in Cyprus.

Data on total area and production per crop per year were extracted from annual agricultural statistics (Cystat 1997-2012), which provide data for 60 different crops. Some of these crops include sub-crops and multi-cropping systems (e.g. 9 greenhouse vegetable crops, 4 fodder crops, 2 main potato planting seasons). Data regarding these management systems were obtained from the Cyprus Department of Agriculture through surveys, Markou and Papadavid (2007) and Cystat (2006), and were used to estimate their annual fraction to the total crop-specific area and production data. Thus, crop water use was computed for a total of 83 different agricultural production systems. The location of crop areas was available in the 2003 agricultural census (Cystat, 2006) for 12 crop groups. It was assumed that the relative distribution of crops within each crop group was the same for all communities and that the relative distribution of crops over the communities remained constant over the study period. Thus, the area of each crop for each community was computed as follows:

$$A_{(crop,com,year)} = \frac{A_{(crop,\,year)} \times A_{(group,com,2003)}}{A_{(group,2003)}} \tag{9}$$

where $A_{(crop,\,com,\,year)}$ is the area of a selected crop, in a selected community and year, $A_{(crop,\,year)}$ is the total area of the selected crop and year from the annual agricultural statistics, $A_{(group,\,com,\,2003)}$ is the area of the crop group that includes the selected crop for the selected community in the 2003 census, and $A_{(group,\,2003)}$ is the total area of this crop group in the 2003 census.

An average irrigated area fraction for each crop over the study period was estimated based on the crop group irrigation fractions available in the annual agricultural statistics (Cystat, 1997-2012), the 2003 census (Cystat, 2006), the cereal (Cystat, 2007-2010) and the vine statistics (Cystat, 2007-2009). Given that no complete information exists regarding the location of the irrigated areas, the same irrigation fractions were used for all 431 communities. Figure 2 provides an overview of the cropland dataset used in the study, indicating the temporal evolution in total irrigated and rain-fed areas. The composition of irrigated and rain-fed areas by crop group is illustrated in Figure 3; note that crop groups are based on FAO (2005) classification standards. Total harvested area was on average 134×10^3 ha, ranging from 148×10^3 ha in 2003 to 103×10^3 ha in 2008. On average, 23% of total harvested area is irrigated. Cereals are the dominant crop group under rain-fed areas (51% on average), with fruits and starchy roots covering most irrigated areas, with an average of 39% and 21%, respectively.

The prevailing irrigation method for each crop was taken from Markou and Papadavid (2007). The fraction of the surface area wetted by irrigation for the different irrigation methods was based on the guidelines given by Allen et al. (1998), i.e. 0.35 for drip systems, 0.70 for micro-sprinklers and 1.0 low-pressure sprinklers.

Soil water holding capacities for the units of the 1:250,000 digital soil map of Cyprus (Hadjiparaskevas, 2005), were obtained from the 0.5 degree Harmonized World Soil database (FAO et al., 2009) and from soil physical information for similar soil units provided by the ESBN (2005). A spatially averaged soil water holding capacity was computed for the area of each community, with the help of a Geographical Information System (GIS).

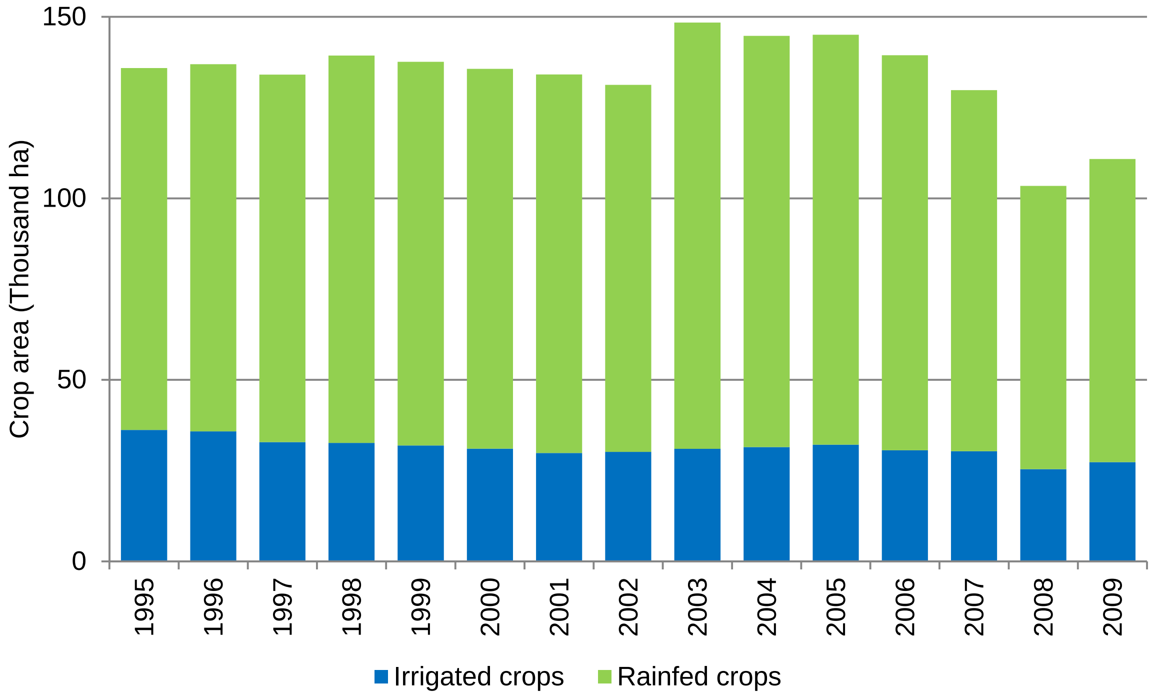

Figure 2. Temporal evolution of irrigated and rain-fed crop areas in Cyprus, for the period 1995-2009.

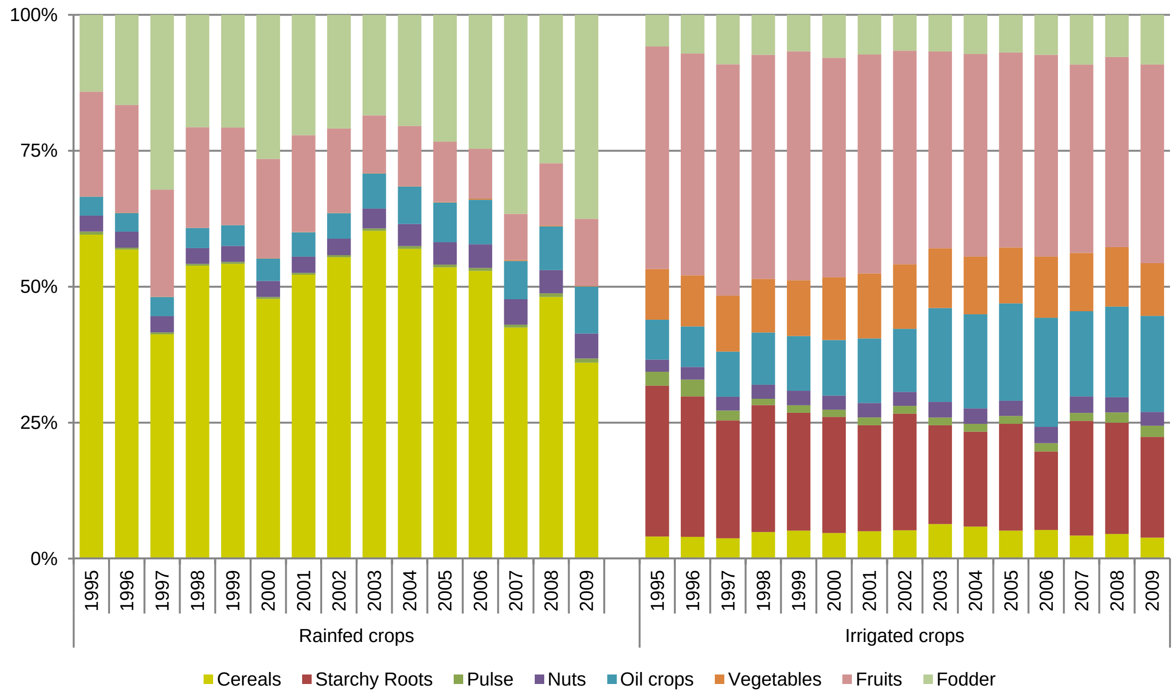

Figure 3. Composition of irrigated and rain-fed crop areas in Cyprus for the period 1995-2009.

Crop coefficients were taken from Allen et al. (1998) and Allen and Pereira (2009). It was assumed that most trees were planted with high or medium density. Crop coefficients for greenhouse crops were taken from the studies of Orgaz et al. (2005) and Bonachela et al. (2006) in Spain. These authors also found reference evapotranspiration inside greenhouses to be slightly higher than half the reference evapotranspiration in the open field (Fernández et al. 2010), therefore a 0.6 factor was used to convert the computed reference evapotranspiration to a value for greenhouses and plastic tunnels. Crop heights (h) and depletion fractions (p) were also obtained from Allen et al. (1998).

Information on planting and harvesting dates and crop development periods for the different agricultural districts in Cyprus have been provided by the Cyprus Department of Agriculture through surveys. Additional information was obtained from local crop-specific studies (Eliades et al. 1995; Metochis 1999, 2006a, 2006b; Josephides and Kyratzis 2007; Kari 2007). Based on the gathered information, average dates were selected to represent the crop's growing environments.

The results of this study were compared with the estimates of Siebert and Döll (2010) and Mekonnen and Hoekstra (2011) for Cyprus. The Siebert and Döll (2010) study covered the period 1998-2002 and was based on the MIRCA2000 dataset (Portmann et al., 2010; Portmann, 2011), which covers 26 crop classes that have been reclassified from the 175 crop-specific total harvested areas available in Monfreda et al. (2008). Thus, the results of the local model for the period 1998-2002 were grouped following the MIRCA2000 classification reported in Portmann (2011, Annex E, pp. 197-199). The Mekonnen and Hoekstra (2011) assessment covered the period 1996-2005 and used the spatial distribution of crop growing areas reported by Monfreda et al. (2008), but the total harvested area per crop was scaled to fit the national crop area reported in FAO (2012). Therefore, the results of this study for the period 1996-2005 were grouped and compared with Mekonnen and Hoekstra (2011) values for Cyprus, following the FAO (2012) crop code classification. It should be noted that the FAO data on total harvested area and production are identical to the data from the national statistics (Cystat, 1997-2012) used in the local study.

Results and Discussion

Spatiotemporal variations in agricultural water use and water footprint

Figure 4 shows the estimated crop water use in Cyprus for the period 1995-2009. For comparative purposes, the mean annual precipitation is added to the graph. The composition of blue and green water use in irrigated and rain-fed areas is provided in Figure 5.

Total agricultural water use was, on average, 506 Mm^3/year, of which 187 Mm^3/year (37%) is attributed to blue water, 62 Mm^3/year (12%) to green water in irrigated crops, and 257 Mm^3/year (51%) to green water in rain-fed crops. Blue water use ranged from 214 Mm^3 in 1995, to 160 Mm^3 in 2009. These values are higher than previous blue water use estimates in Cyprus. Savvides et al. (2001) estimated a total irrigation demand of 175 Mm^3 for the year 2000, using 30-year average class "A" pan evapotranspiration for 10 crop groups. Karavokyris et al. (2011), on the other hand, used average irrigation requirements, adjusted for elevation, and the spatial distribution of irrigated crops in 2008, to estimate a total irrigation demand of 152 Mm^3 for 2011. The differences can be attributed to the higher spatial and temporal detail used by the current model, especially the variable contribution of precipitation. Furthermore, both studies neglected the irrigated share of cereal and fodder crop areas, which on average used 20 Mm^3 of blue water per year.

In contrast to the relatively low temporal variability in blue water, green water use varies widely over time. The total average green water - i.e. both in irrigated and rain-fed cropland - was 339 Mm^3/year, and ranged from 441 Mm^3 during the wettest year of the 15-year period (561 mm precipitation in 2003), to 169 Mm^3 in the driest year (272 mm precipitation in 2008). The spatial distribution of blue and green water use during these two seasons is given in Figure 6. The high blue water use in coastal areas, associated with potato, citrus and vegetable plantations, did not change substantially between wettest and driest years of the 15-year period. On the contrary, there was significant reduction in green water use during the driest year (Figure 6d), especially in the central plain that are used mainly for barley production.

This substantial difference in green water use is attributed to the highly variable precipitation in Cyprus, which affects the harvested area of rain-fed crops. The most obvious example is that of cereals, which on average cover 51% of rain-fed cropland and utilise 39% of green water. During the wet year, green water use in rain-fed cereals was 78% above the 15-year average, whereas it was 54% below average during the dry year; this translates to 33% above average harvested area in 2003 and 29% below average in 2008. The effects of variable precipitation can also be assessed by comparing the crop-specific water footprints and yields between wet and dry seasons (Figure 7). For example, the water footprint of rain-fed wheat was two times higher during 2008 compared to 2003, which is explained by the very low yields during the dry year (0.4 ton/ha, compared to 1.9 ton/ha). On the other hand, the yields of irrigated crops, such as potatoes, tomatoes and oranges remained almost unchanged between wet and dry years, yet the share of blue water use per ton of output was higher during the dry year. Olives keep their dry-resistant reputation, as the yield of rain-fed olives was not affected during the dry season, and was even higher in irrigated groves, hence the lower water footprint in 2008.

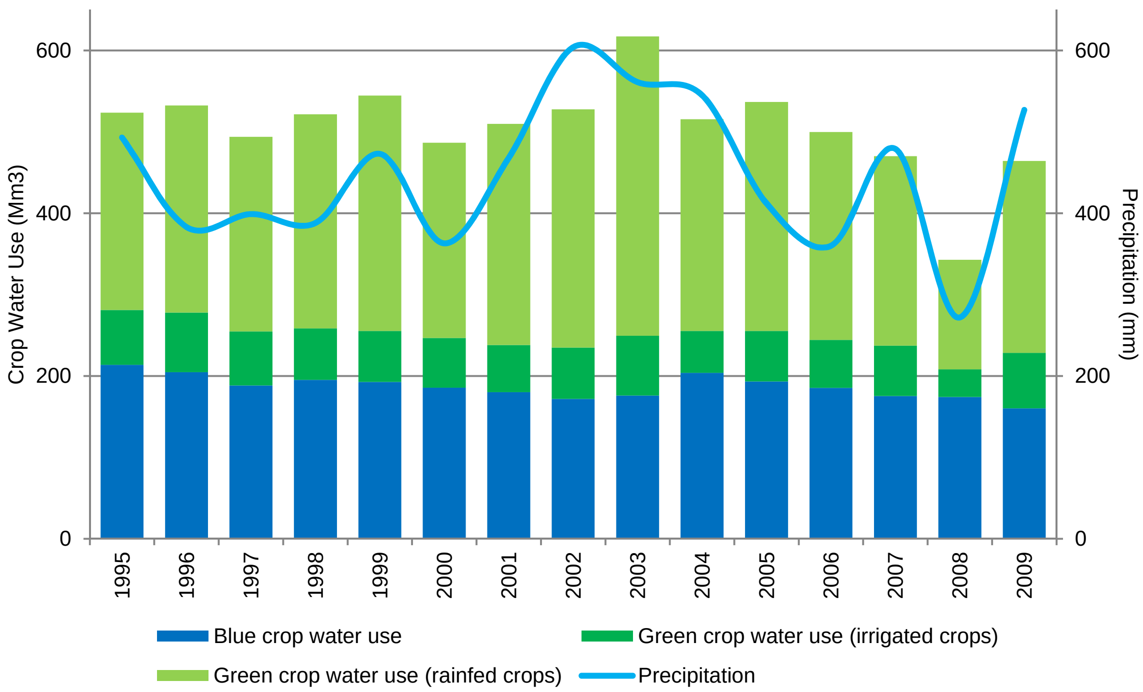

Figure 4. Estimated blue and green crop water use for the period 1995-2009.

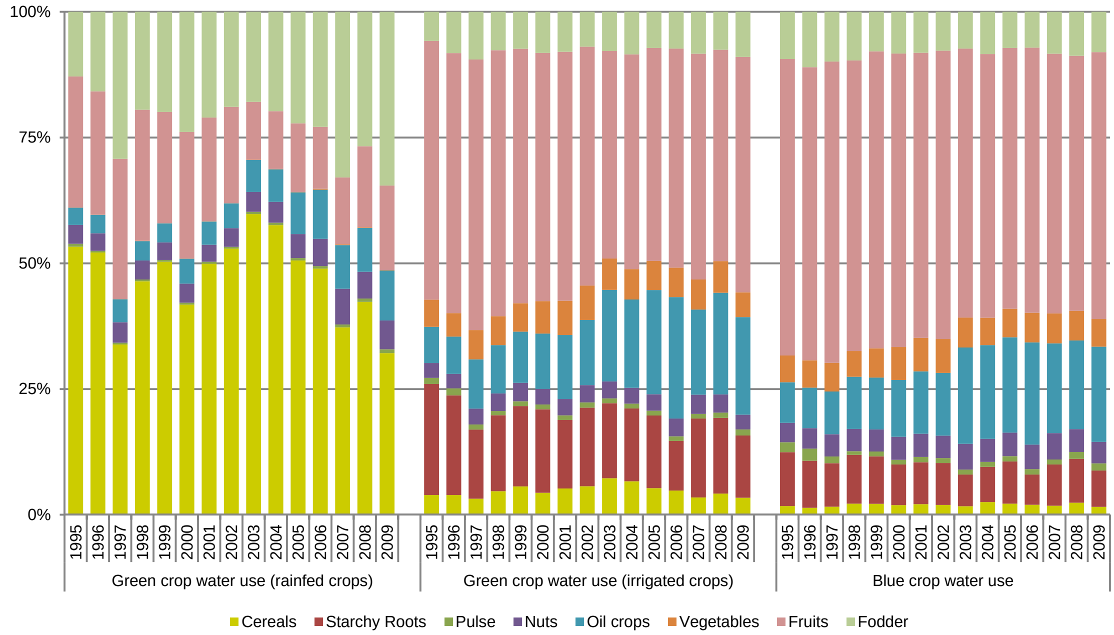

Figure 5. Composition of blue and green crop water use for the period 1995-2009.

Global vs. local estimates

Table 1 shows the results of the local model and the estimates of Siebert and Döll (2010) and Mekonnen and Hoekstra (2011) for Cyprus. The estimates of Siebert and Döll (2010) for Cyprus include 5 crops (wheat, maize, barley, potatoes and grapes) and 5 broad crop classes (pulses, citrus, fodder grasses, other perennials and other annuals). Compared to the results of the local model, the Siebert and Döll (2010) estimates are 94% lower for green water use in rain-fed crops, 24% higher for green water use in irrigated crops, and 41% higher for blue water use. Furthermore, the low r^2 values, especially for total green water use (r^2 = 0.07, Figure 8a) are indicative of large discrepancies between the two estimates, which are attributed to different input data and modelling assumptions. For instance, Siebert and Döll (2010) used the growing areas reported in the MIRCA2000 dataset, which are different from the values reported in the agricultural statistics used in the current study. In particular, the total harvested area for Cyprus in the MIRCA2000 dataset (Portman, 2011, App. I, p.156) is 42×10^3 ha, of which 13% is rain-fed and 87% is irrigated. However, based on the agricultural statistics, the total average harvested area in Cyprus for the period 1998-2002 was 136×10^3 ha, of which 77% is rain-fed and 23% is irrigated (Figure 2). The large share of irrigated cropland in the MIRCA2000 dataset is due to the assumption that all crops in Cyprus, other than maize and fodder grasses, are fully irrigated. This assumption is principally attributed to the planting dates and the length of cropping period used. For example, it is assumed that the growing period for wheat in Cyprus is between April and September (Portman, 2011, App. I, p.156), which are generally the dry months in Cyprus, therefore it is assumed that wheat is cultivated under irrigated conditions. Furthermore, barley is assumed to be irrigated during winter months (Portman, 2011, App. K, pp. 90-92). In reality, the growing period for wheat is between November and February, and the irrigated share of both cereal crops is very small according to the agricultural statistics; 2% for barley and 9% for wheat (Figure 3). Hence adopting the assumptions and crop specifications of MIRCA2000, Siebert and Döll (2010) underestimate the total green water use and overestimate blue water use. Other factors such as crop parameters, soil and climate data, may also determine the output of crop models and are further discussed below.

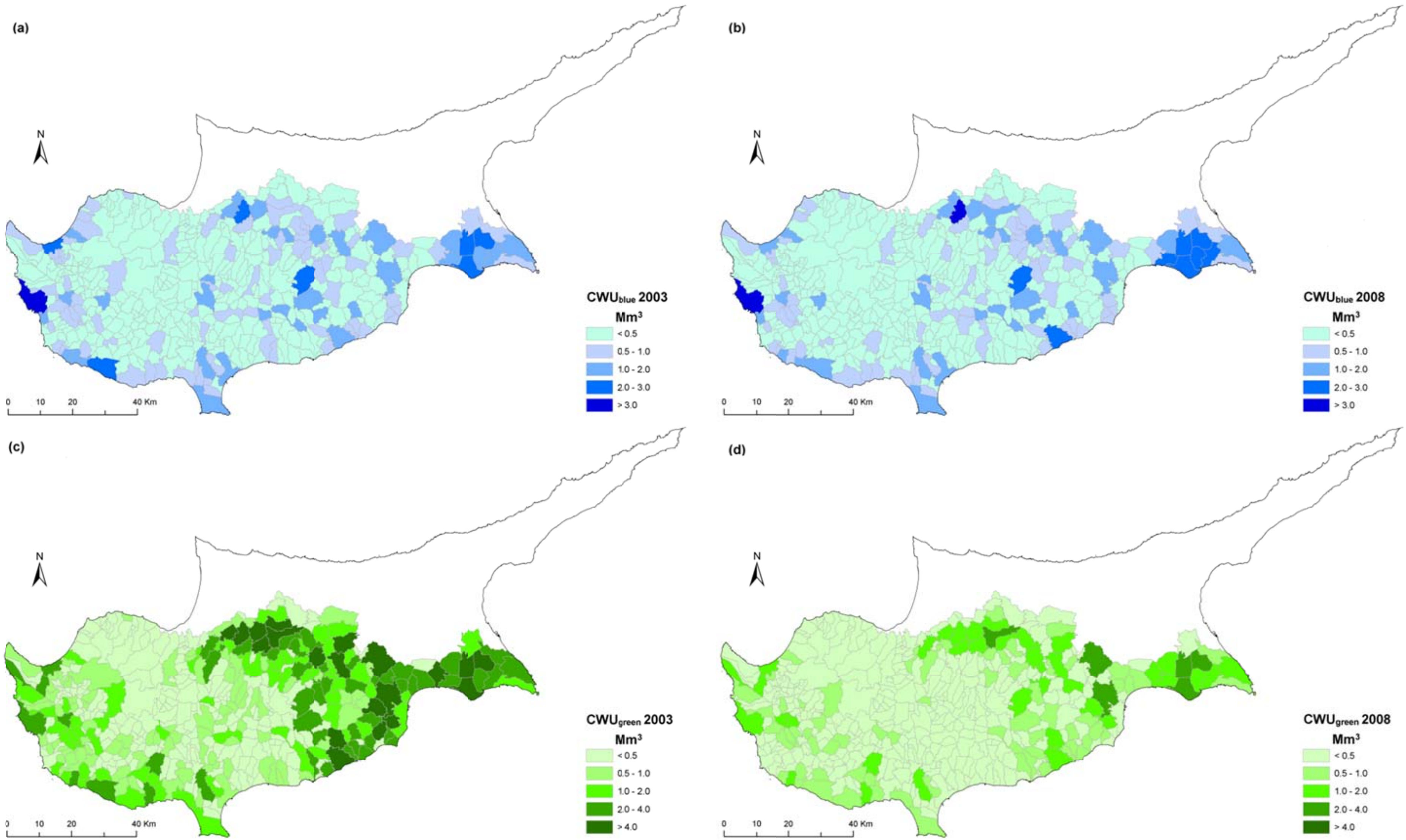

Figure 6. Spatial distribution of blue and total green crop water use in Cyprus for the years 2003 (wet) and 2008 (dry).

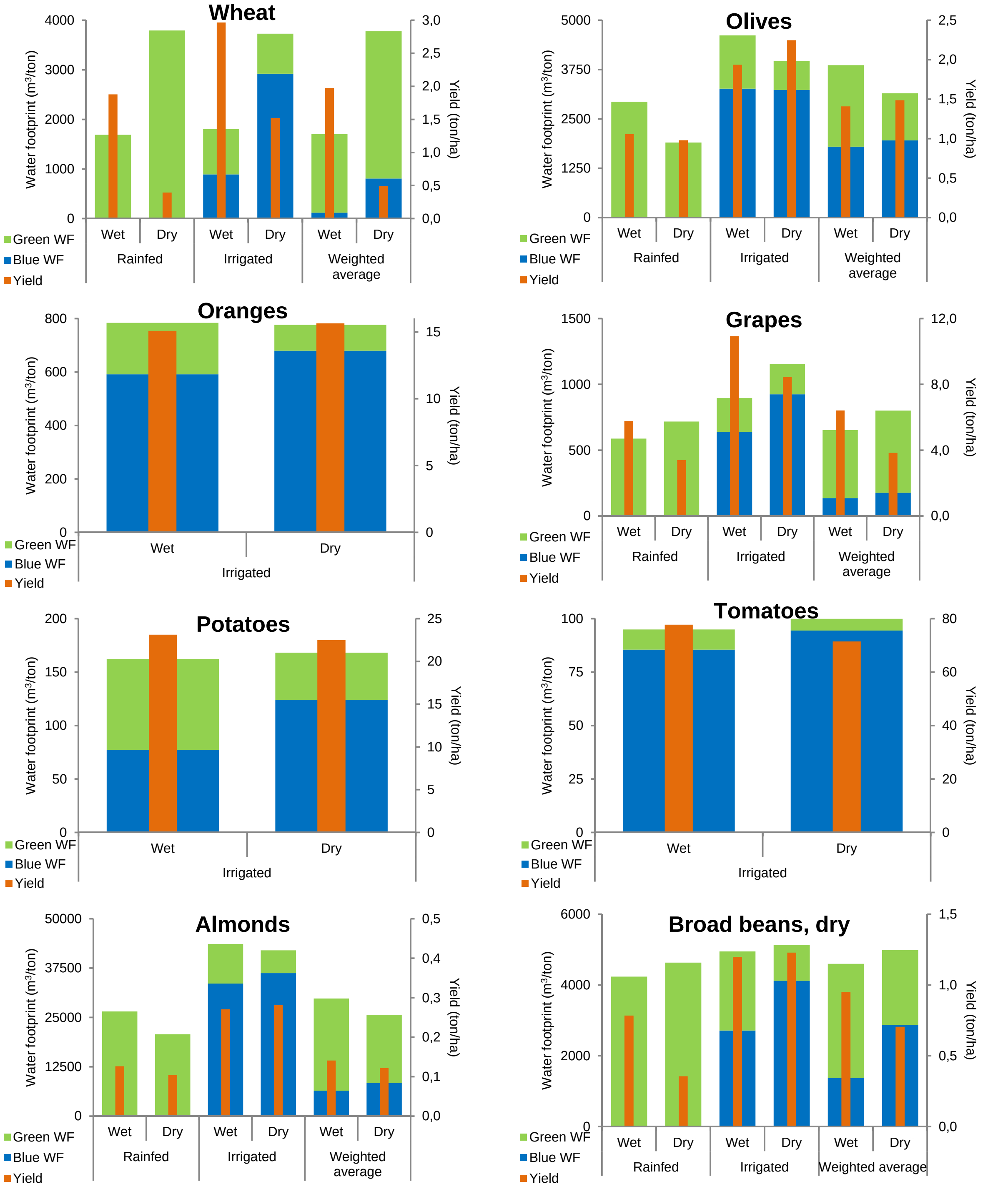

Figure 7. Water footprint and yield for selected crops under rain-fed and irrigated conditions during the wettest (2003) and driest (2008) years of the 15-year period examined.

Table 1. Comparison between the crop water use results from this study and from global assessments

Study	Period	No. of crops	Crop water use in Cyprus (Mm^3/year)				
			Green* (RF)	Green** (IR)	Green (RF+IR)	Blue	Total
Siebert and Döll (2010)	1998-2002	10 groups	16	77	92	262	354
This study			271	62	333	185	518
Mekonnen and Hoekstra (2011)	1996-2005	60 primary	204	135	340	268	608
This study			276	63	339	187	519

* Green RF: green water use in rain-fed crops; ** Green IR: green water use in irrigated crops.

The Mekonnen and Hoekstra (2011) study includes 60 primary crop estimates for Cyprus and covers the period 1996-2005. A comparison with the estimates of this study shows that the Mekonnen and Hoekstra (2011) results are 26% lower for green water use in rain-fed crops and 114% higher for green water use in irrigated crops. The surprising finding was the almost exact estimate in total green water use between the two studies; 340Mm^3/year in Mekonnen and Hoekstra (2011) and 339 Mm^3/year in this study. At crop level, the two studies also correlate well in terms of total green water use (r^2 =0.88, Figure 9a) but the Mekonnen and Hoekstra (2011) results were consistently higher (y=0.89x), except for 11 out of 60 primary crops. This finding can be attributed to the similar harvested areas used by the two studies. Regarding blue water use, the Mekonnen and Hoekstra (2011) estimate was 43% higher with poor correlation per crop (r^2 =0.05, Figure 9b). The highest differences occur in tree crops, such as almonds and carobs; Mekonnen and Hoekstra (2011) assume full irrigation for both crops, whereas the actual irrigation fractions are 10% and 0%, respectively. Furthermore, the total blue water use between the two global studies for Cyprus is quite similar; 262 Mm^3/year in Siebert and Döll (2010) and 268 Mm^3/year in Mekonnen and Hoekstra (2011). The fact that Mekonnen and Hoekstra (2011) have also used the MIRCA2000 irrigation fraction of harvested crop areas, as well as the planting dates and growing seasons for certain crops (not specified which crops and for which countries), can explain the similarities between the two global studies and the difference with the results of the local model.

Figure 10 compares the green, blue and total water footprints as estimated in this study, with the results from Mekonnen and Hoekstra (2011). The trend line for green water footprint (y=0.99x) almost fits the 1:1 line, however the r^2 value (0.46) is low. For blue and total water footprints the r^2 values are relatively high (0.82 and 0.86, respectively) indicating good correlation between the two estimates, yet the slope of the trend lines show that the Mekonnen and Hoekstra (2011) values are overall higher than the results of this study. In general, the results of Mekonnen and Hoekstra (2011) correlate better with the results of this study, than the Siebert and Döll (2010) estimates, partly due to an identical dataset regarding total harvested crop area and production.

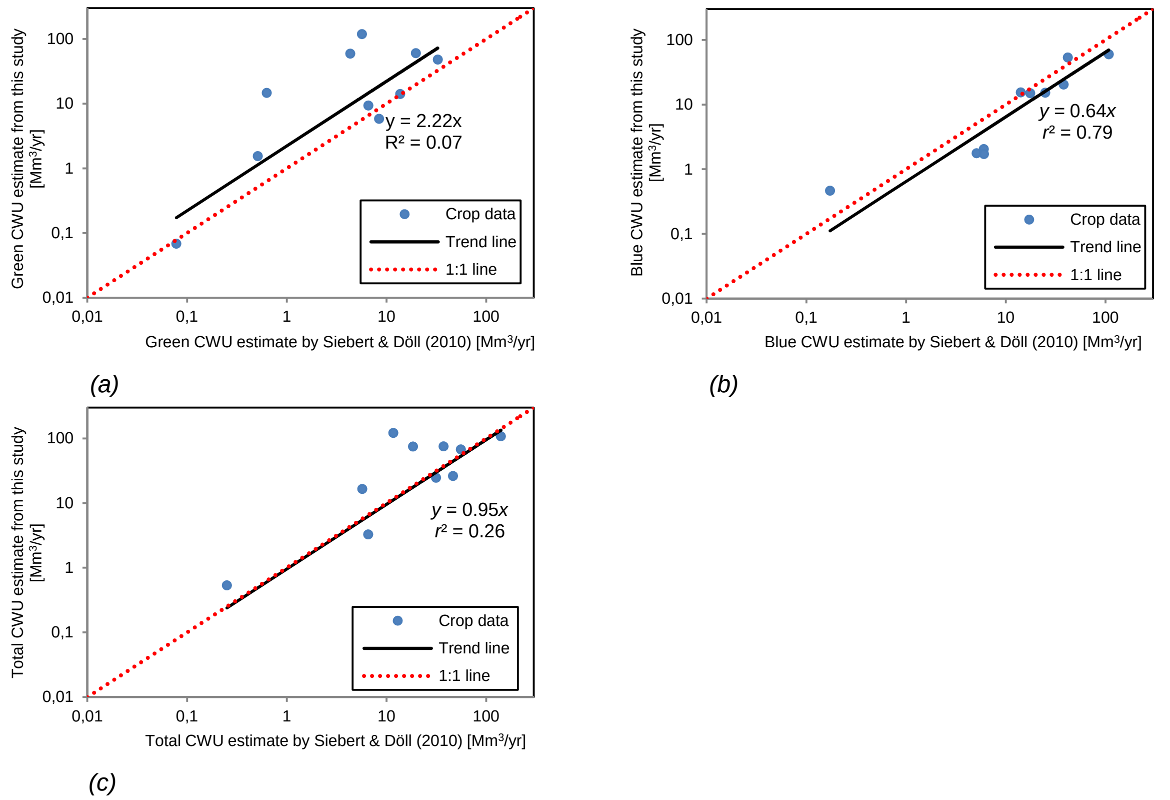

Figure 8. Comparison of total green (RF+IR), blue and total crop water use in Cyprus as estimated in this study with Siebert and Döll (2010), for the period 1998-2002.

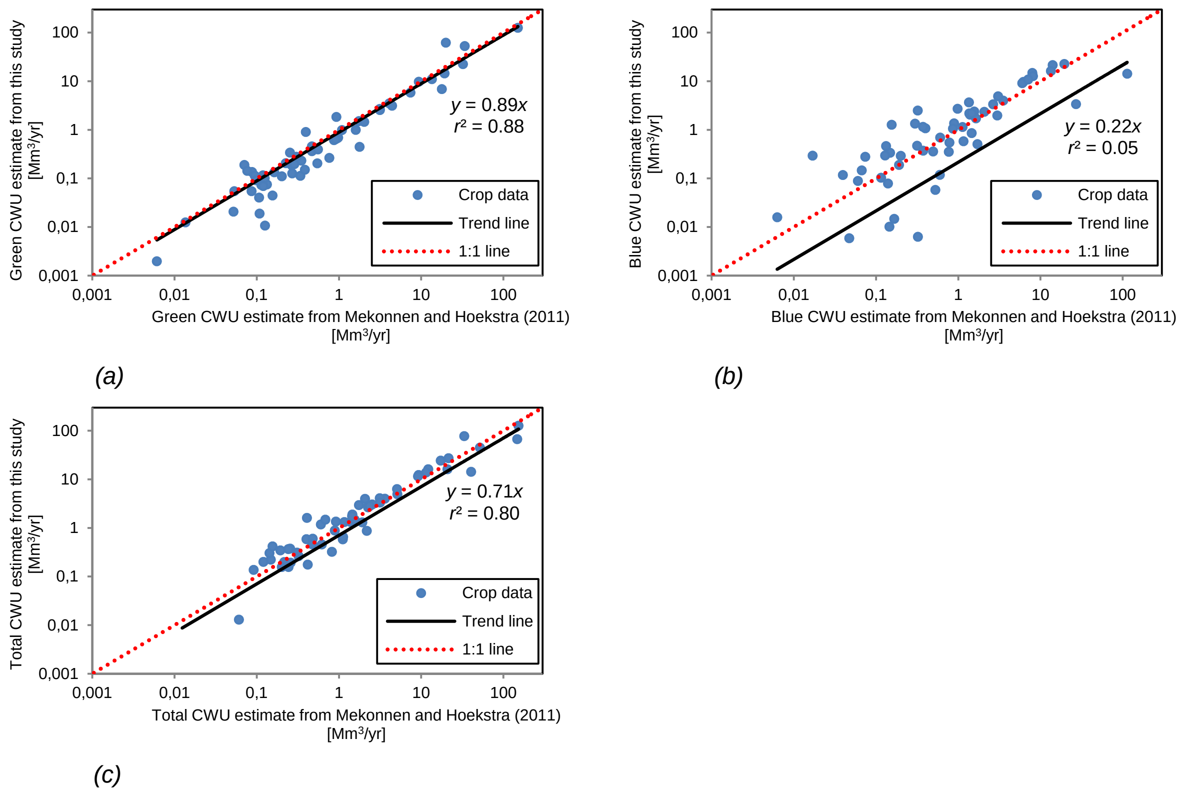

Figure 9. Comparison of total green (RF+IR), blue and total crop water use in Cyprus as estimated in this study with Mekonnen and Hoekstra (2011), for the period 1996-2005.

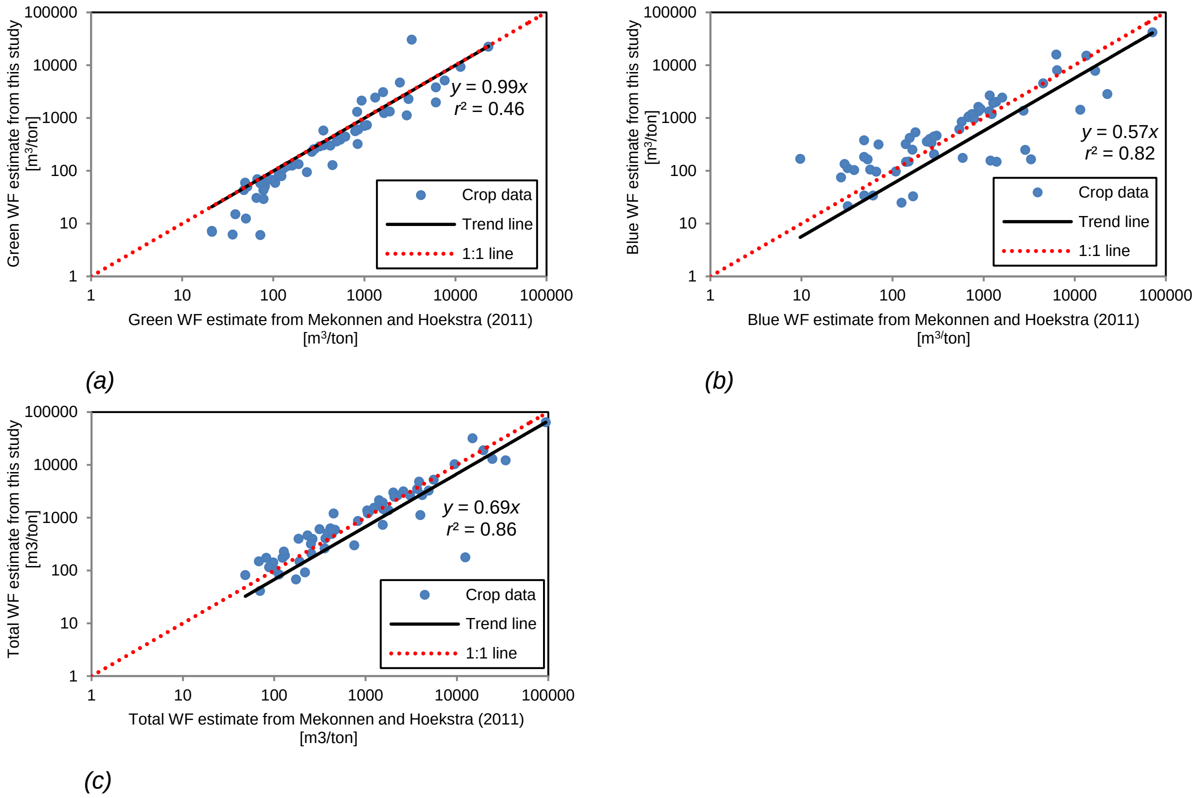

Figure 10. Comparison of green, blue and total water footprint for primary crops in Cyprus as estimated in this study with Mekonnen and Hoekstra (2011), for the period 1996-2005.

Limitations and modelling uncertainties

The accuracy of soil water balance models is determined by modelling parameters and assumptions, and the quality of input data. The present study relied on the spatial location of crop groups from the agricultural census and the national harvested areas of all crops, which were readily available in the annual agricultural statistics. In general, the main scope of agricultural statistics is to accurately measure economic variables. Water use estimations are therefore inherently subject to the quality and accuracy of the annually reported data on harvested cropland. Furthermore, blue water use is estimated based on the assumption that irrigation requirements are fully met. This condition may not always hold, especially during very dry years when blue water availability is low. At the same time however, farmers may apply more irrigation than required by the crop; potatoes for example are irrigated during winter months to minimise frost susceptibility. Therefore it is assumed that blue water demand is approximately equal to actual blue water use.

Overall, the quality of spatial and temporal data used in this study is higher and improves previous estimates in Cyprus. To this end, the results of the model can contribute and guide policy decisions towards sustainable water resource management. The development of spatial databases can potentially enhance the accuracy of future estimates. In addition, the uncertainty level of results can be examined in future estimates by applying a sensitivity analysis of the model output to the parameter values and data used.

The discrepancies revealed in the comparison of global and local estimates are associated with the datasets used by each model. With regards to the input data used in this study, it is safe to assume that the results provided are closer to reality than those of global models. In general, large-scale models rely on a number of assumptions due to lack of data, thus the uncertainty of model results is high (Mekonnen and Hoekstra, 2011; Döll et al, 2008). As discussed above, certain differences between global and local estimates are attributed to the data regarding total harvested area and irrigated fractions for specific crops. Furthermore, planting dates and the length of cropping seasons can also affect the overall outcome, as they determine crop water requirements and the amount of applied irrigation (Liu and Yang, 2010). In fact, McCann et al. (2008) found that the length of the cropping period is the most sensitive parameter for crops cultivated under semi-arid Mediterranean conditions. The climate data used in global models is also a source of input uncertainty. According to Döll et al (2008) the uncertainty in quantifying precipitation is the major challenge for large-scale modelling. Soil is another important parameter controlling soil water balance. The soil water holding capacities in global grid-based assessments is derived based on the dominant soil type. Mekonnen and Hoekstra (2011) note that this assumption is not always valid, since farmers usually cultivate on the best available soils, which may have different water holding capacity than the dominant soil type of each grid cell. This is particularly the case in mountainous regions, where agriculture is limited to valley deposits or on terraces with deeper soils (Wriedt et al., 2009). Bruggeman et al. (2012) found 17% higher green water use and 12% lower blue water use when comparing the best soil map estimates in Cyprus (40-150 mm available water holding capacity) to a uniform soil water holding capacity (150 mm), representing the potential soil and water conservation practices (terracing) on shallow soils. Other crop parameters such as the rooting depths also affect the model outcomes (Mekonnen and Hoekstra, 2011).

Having in mind the uncertainties, the input data limitations and the simplification of model parameters, the results of global studies need to be interpreted with care. Although global models cannot be used for policy formulation, they provide average estimations which can be useful for awareness-raising and for cross-country comparisons. Furthermore, the result of global assessments can be used for projecting future trends regarding water use.

Conclusion

The formulation of appropriate policies towards improving water resource management requires precise information on water use at the catchment level. Soil water balance models provide the means to estimate agricultural water use, in the absence of metered data. The objectives of this paper were to present the model developed to quantify the water footprint of crop production in Cyprus for the period 1995-2009, and to compare its output with the estimates of global assessments for Cyprus.

Using local data and knowledge, our model captured the inter-annual effects of climate variability on blue and green water use over space and time, as well as the effects on crop yield and harvested cropland. The results show that on average, total agricultural water use in Cyprus was 506 Mm^3/year, of which 63% is attributed to green water and 37% to blue water. Blue water use ranged from 160 Mm^3/year to 214 Mm^3/year, while green water ranged from 169 Mm^3 during the driest years, to 441 Mm^3 during wettest years. With regards to the decreasing precipitation in Cyprus due to climate change, and the limited availability of blue water resources, the results of the model can potentially guide policy decisions to a sustainable green-blue water use strategy. The accuracy and precision of future estimates can be enhanced with the development of spatial databases.

The comparison between the results of this study with global water use models revealed that the Siebert and Döll (2010) estimates for Cyprus were 72% lower for total green water use and 41% higher for blue water use. In the case of Mekonnen and Hoekstra (2011), the total green water use was identical with the result of the local model, but blue water use was 43% higher in the global model. The discrepancies between the results of global and local models are attributed to the different input data regarding harvested cropland and fractions of irrigated areas, as well as planting dates and the length of cropping seasons. Other input parameters and assumptions adopted by each model, such as climate and soil data, may also explain the difference between global and local model estimates. In general, global consumptive water use studies rely on a number of assumptions to deal with the limitations regarding data availability and quality, thus the uncertainty of model results is high. Considering these drawbacks, the results of global studies cannot be used for policy formulation and need to be carefully interpreted. At the same time, the output of global models is particularly useful for cross-country comparisons and can be used for projecting future water use trends, at the global level.

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2. Sectoral and regional analysis of the impacts of China's international trade on its water resources and uses

Zhuoying Zhang[1,2], Minjun Shi[2,3], Hong Yang[4]

[1] Academy of Mathematics and Systems Science, Chinese Academy of Sciences, 100190, Beijing, China.

[2] Graduate University of Chinese Academy of Sciences, 100049, Beijing, China

[3] Research Centre on Fictitious Economy & Data Science, Chinese Academy of Sciences, 100190, Beijing, China

[4] Swiss Federal Institute of Aquatic Science and Technology, 8600, Dübendorf, Switzerland

Abstract

China is under severe water pressure due to the rapid economic development, growing population and expanding international trade. This study provides an insight into the impacts of China's international trade on its water resources and uses. The virtual water flows associated with China's international trade are quantified within an input-output framework. The analysis is based on the data for 2007. The results show that China as a whole is a net virtual water exporter of 68.2×10^9 m^3/year, accounting for 3.1% of its renewable water resources and 11.5% of its total water use. Water scarce regions, particularly the Huang-Huai-Hai region, tend to have higher percentages of virtual water export relative to their water resources and uses. For individual sectors, major net virtual water exporters are those where agriculture provides raw materials in the initial process of the production chain. The results suggest that China's economic gains from being the world's 'manufacturing factory' have come at a high cost to its water resources in quantity and quality. It is important for China to incorporate the virtual water trade into its economic development strategy to ensure a sustainable use of regional and national water resources.

Introduction

As the "world's manufacturing factory", China is obtaining economic benefits from the international trade, particularly the huge surplus of export. But the gains are made at high costs to its water resources in quantity and quality. China uses a large portion of water for the production of commodities for export. The intensification of water scarcity in China can have impact on its international trade, an important pillar of its rapid economic growth since the late 1970s. Understanding the impacts of China's international trade on its water resources and uses is of importance for formulating appropriate water strategies to support the long term economic development of the country.

Traditional water use statistics provide the freshwater intake in individual sectors. In essence they reflect only the direct water consumption/use (DWC) to produce the final products of individual sectors. However, the production chain of products in a sector may go through several sectors, Take the sector of clothing as an example, the DWC of clothing only includes the portion used in the clothing factory. The part of the water used for the production of the raw material (i.e. cotton) is not included. The concepts of virtual water and water footprint overcome this shortcoming. They account for the sectoral total water use (TWU), i.e., the water consumed throughout the whole production chain of a sector. For the sector of clothing, TWU includes the water used during the raw material production and processing, textile manufacturing and in clothing factory. However, accounting for TWC of a sector is often complex because of the difficulty in quantification of the interconnections of water uses across sectors.

The input-output (IO) model is a technique quantitatively depicting the interconnections and interdependences of economic units. Since it can specify how the substances flow among sectors through supplying inputs for the outputs in the economic system, the input-output framework has been recently applied to the virtual water accountings (Zhao et al., 2009; Dietzenbacher and Velazquez, 2007; Wang and Wang, 2009). However, the previous studies lack the specification of the origins of the virtual water export which are important for identifying the prominent regions influencing the national virtual water trade patterns and the regions which are significantly affected by their international trade patterns.

This paper aims to fill in the gap by conducting an IO-based virtual water analysis. It scaled down to the sectoral and provincial levels to trace the origins and destinations of virtual water flows associated with the international trade. The results of this study contribute to a better understanding of China's water challenges and provide insight for formulating policies to tackle the problems. The main content of this paper includes:

- Quantifying the virtual water flows associated with China's international trade in the framework of the input-output model;
- Identifying the sources of the virtual water exports at the provincial level for different economic sectors;
- Specifying the impacts of virtual water trade on national and regional water resources and uses.

Data and Methodology

Data

The data foundation for the analysis is the 2007 regional IO tables of 30 regions in China (National Bureau of Statistics of China, 2010) which are hitherto the latest available data we can use since the provincial IO tables are officially published every 5 years. The 30 regions include 22 provinces, 4 municipalities and 4 autonomous regions in mainland China. Hong Kong, Macao, Taiwan and Tibet are not included due to data unavailability. For simplicity, these 30 administrative entities are all called provinces in this study.

The basis for the calculation of sectoral water footprint is the amount of water use per monetary unit of a sector which is reflected by direct water use coefficient (DWUC) and total water use coefficient (TWUC). The DWUC reflects the direct water intensity at the last stage of the production chain (the operational stage for a business or a factory), whereas the TWUC reflects the water intensity throughout the whole production chain. In this study, the detailed methodology in determining DWUC can be found in Zhang et al., 2011a.

In this study, water resources, water uses and virtual water trade concern only blue water, i.e., the surface and ground water. Soil moisture, the so-called green water is not considered. The definition of blue and green water follows that by Falkenmark and Rockström (2004). The detailed discussion on excluding green water can be found in Zhao et al., 2010 and Zhang et al., 2011b.

In the agricultural sector, part of the water use is returned to the natural water systems through percolation. Considering that this return flow may be available for downstream users, the calculation of the agricultural water use and virtual water trade deducted the return flow by multiplying the direct water use coefficient with the water consumptive use ratio which is available from the Water Resources Bulletin of the six major river basins (Haihe, Huaihe, Yellow River, Yangzi, Pearl River, Songliao River (River Basin Water Conservancy Commissions, 2008). In the industrial sectors, the water use refers to the freshwater intake. The recycle and reuse of water is not included in the water use accounting. Wastewater discharge is not deducted from the industrial water use because the polluted water may not be used again without treatment. Besides, lacking information on the actual discharge rate and the pollution intensity in each industrial sector also adds difficulties in considering the return flows.

Methodology

In the Virtual Water accountings, DWUC has to be derived through Eq. 1 to combine the monetary trade with the associated water use.

$$\mathbf{w} = \left[\omega_j\right], \quad \omega_j = \frac{w_j}{x_j} \tag{1}$$

where $\mathbf{w}$ is the vector of DWUC; ω_j is the DWUC of sector j, calculated by dividing the water use of sector j (w_j) by total output of sector j (x_j).

Then TWUC can be obtained by multiplying DWUC (ω_j) with the Leontief inverse matrix $\left[b_{ij}\right]$.

$$\mathbf{d} = \left[\delta_j\right], \quad \delta_j = \sum_i \omega_i \times b_{ij} \tag{2}$$

where $\mathbf{d}$ is the vector of TWUC, including not only the water needed for the production of the product itself, but also for the production of the materials and components that go into the process. b_{ij} denotes how much output of sector *i* is required to meet one monetary unit of the final demand of sector j.

The virtual water export and import can be computed as

$$\mathbf{u} = \left[u_j\right], \quad u_j = \delta_j \times e_j \tag{3}$$

$$\mathbf{v} = \left[v_j\right], \quad v_j = \delta_j \times m_j \tag{4}$$

where $\mathbf{u}$ and $\mathbf{v}$ are the vectors of the virtual water export and import by sectors; e_j and m_j are respectively the export level and import level of sector j.

Results and discussion

Virtual Water Trade in Individual Sectors

Table 1 shows the DWUC, TWUC and virtual water trade of individual sectors. The disparities between DWUC and TWUC are small in some sectors but large in some others, reflecting different characteristics of water uses in the production chain of each sector. In general, 1-AGR and 16-EGW are direct water use dominated sectors, reflected by the high proportions of DWUCs in TWUCs. In contrast, most manufacturing sectors have large indirect water uses. For 3-FTP, 5-CLT, 6-SAF, 12-MEQ, etc., over 95 percent of the water use takes place in an indirect way, i.e., in the previous processing stages prior to the final stage. For example, the clothing sector had DWUC at 29 m^3/104USD, and TWUC at 2297 m^3/104USD in 2007. This means that about 99% of the water use took place in the supply chain of the clothing industry.

For individual sectors, 1-AGR has the highest water-intensity, with TWUC of 8858 m^3/104 USD. This is followed by 16-EGW, where TWUC is 6303 m^3/104 USD in 2007. The other sectors with relatively high TWUC are 3-FTP, 4-TXG and 19-REH, which are indirect water use dominated, meaning that the main water uses incurred in the supply chain, typically through the raw materials from the agricultural sector.

In 2007, the total amount of virtual water import of China is 74.5×109 m^3/year, whereas the total virtual water export is 142.6×109 m^3/year. Hence, China turns out to be a net virtual water exporter of 68.2×109 m^3/year in view of the whole national economy.

For individual sectors, the virtual water trade balance varies. Sector 1-AGR, 8-PEP, 12-MEQ, 16-EGW, 17-CTR, 20-OSV are the net importers of virtual water. The other 14 sectors are net exporters.

14-ETE, 5-CLT, 11-MSP, 4-TXG and 9-CHM are the five major net virtual water exporters. These sectors are the mainstay industries in China, greatly contributing to China's role as the "world manufacturing factory". Their total net virtual water export amounts to 61×109 m^3/year, or 89% of the total net virtual water export of the country.

It is worth noting that 3-FTP and 4-TXG are typical downstream industries of agriculture. Although the agricultural sector is a net importer in China, its downstream industries are not (Table 1). The situation suggests that part of the imported virtual water from agriculture is re-exported through the exports of products in the downstream sectors.

Regional variations in virtual water trade

The virtual water trade patterns appear substantial spatial variations due to the significant discrepancies in natural conditions and economic development levels among regions. Table 2 provides the quantity of virtual water trade of individual provinces associated with their international trade.

Table 1. Detailed results of sectoral virtual water trade accounting (2007)

	Sectors	DWCC	TWCC	Virtual Water Export	Virtual Water Import	Net Virtual Water Export
		$m^3/10^4$ USD	$m^3/10^4$ USD	10^6 m^3	10^6 m^3	10^6 m^3
1-AGR	Agriculture	6930	8858	18212	21137	-2924
2-CMP	Coal mining and processing	168	1051	678	123	555
3-FTP	Food and tobacco processing	170	3925	7288	5137	2151
4-TXG	Textile goods	161	3898	6329	313	6015
5-CLT	Clothing	29	2297	19392	1363	18029
6-SAF	Sawmills and furniture	14	2096	5239	402	4837
7-PAP	Paper and products	477	2399	4928	753	4175
8-PEP	Petroleum processing	131	1079	1139	3167	-2028
9-CHM	Chemicals	252	1789	10430	4653	5777
10-NMP	Non-metal mineral products	120	1382	2170	434	1736
11-MSP	Metal smelting and products	216	1628	13278	4493	8785
12-MEQ	Machinery and equipment	25	1137	6085	6990	-905
13-TRE	Transport equipment	31	1103	3735	1334	2400
14-ETE	Electric equipment, telecommunication equipment	16	1051	32067	10028	22039
15-OMF	Other manufacturing	26	1237	1532	736	796
16-EGW	Electricity, gas and water production and supply	4315	6303	1325	7090	-5765
17-CTR	Construction	24	1196	481	2352	-1871
18-WRP	Wholesale and retail trade and passenger transport	210	929	5074	1431	3643
19-REH	Restaurant and hotel	901	3311	1184	291	893
20-OSV	Other services	123	858	2067	2229	-163
	Total			**142634**	**74457**	**68177**

Source: Zhang et al., 2011a.

Table 2. Virtual water trade at the provincial level (2007) (10^6 m^3/year)

Provinces		Virtual water export	Virtual water import	Net virtual water export
1	Beijing	2000	1737	263
2	Tianjin	1111	472	638
3	Hebei	1602	843	760
4	Shanxi	377	361	16
5	Inner Mongolia	1836	753	1082
6	Liaoning	2748	1089	1659
7	Jilin	1725	3057	-1332
8	Heilongjiang	485	434	51
9	Shanghai	12185	10079	2106
10	Jiangsu	28816	16616	12200
11	Zhejiang	11785	2728	9057
12	Anhui	1386	573	812
13	Fujian	6572	1986	4587
14	Jiangxi	1383	4722	-3339
15	Shandong	7347	3840	3508
16	Henan	275	219	56
17	Hubei	832	556	276
18	Hunan	1819	1270	550
19	Guangdong	32544	10754	21790
20	Guangxi	1687	1817	-130
21	Hainan	466	669	-203
22	Chongqing	383	266	117
23	Sichuan	899	541	357
24	Guizhou	691	516	175
25	Yunnan	532	759	-227
26	Shaanxi	337	112	224
27	Gansu	7512	6438	1074
28	Qinghai	150	234	-84
29	Ningxia	4346	113	4233
30	Xinjiang	8804	905	7900
Total		142634	74457	68177

Except for Jilin, Jiangxi, Guangxi, Hainan Yunnan and Qinghai, all the other provinces are net virtual water exporters. Guangdong is the largest net virtual water exporter with the net virtual water export of 21.7×109 m^3/year, accounting for 32% of the total net virtual water export of China. Zhejiang, Jiangsu, and Xinjiang are also important virtual water exporters, accounting for the total net virtual water export of 13.2%, 17.9%, and 11.6%, respectively.

Water resources endowments vary across provinces in China. Figure 1 shows the major exporting sectors in 4 extremely water scarce provinces, Beijing, Tianjin, Hebei, and Shandong. The per capita renewable water resources availability in these provinces is below 150 m^3/capita (National Bureau of Statistics of China, 2008).

The net virtual water export in these 4 provinces accounts for 8% of the total net virtual water export of China, whereas the sum of their water resources is only 2.2% of the national total.

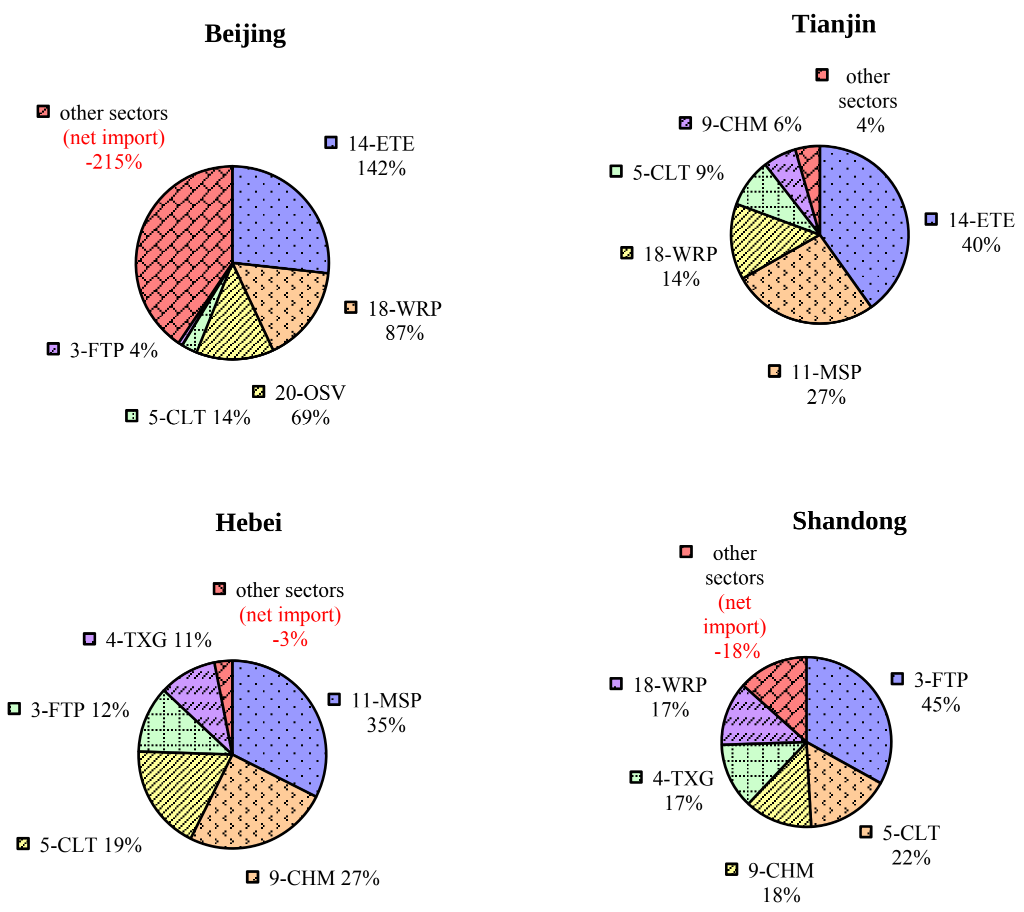

Figure 1. The major net virtual water exporting sectors in the selected water scarce provinces (2007)

Figure 1 presents the share of the first 5 major net virtual water exporting sectors in total net virtual water export in the selected provinces. Apart from 4-TXG and 5-CLT, there are significant variations in other major sectors in the selected provinces. They reflect the sectoral specialization in these provinces. For example, the net virtual water export in Beijing mainly concentrates in the sectors related to services (18-WRP and 20-OSV). The virtual water export of services refers to the water used in providing services to the people coming from overseas. As Beijing is the capital city visited by many foreigners every year, the service related sectors are the main contributors to its virtual water export. The share of the remaining sectors is -215%, meaning that the net virtual water import in these sectors offsets 215% of the net virtual water export in Beijing. This considerably high rate of net virtual water import confirms the effects of Beijing's external virtual water import in balancing the water loss through product export. In Tianjin, 14-ETE and 11-MSP have large shares in net virtual water export. This corresponds to Tianjin's developed manufacturing foundation and its favourable port transportation conditions. In both Hebei and Shandong, the net virtual water exports are highly concentrated in their five major exporting sectors, which account for 103% and 118% of the total export, respectively.

Impacts of virtual water trade on domestic water resources and water uses

Given China's export of 68.2×109 m3 of virtual water and the total water resources of 2200×109 m^3/year (average of 2002-2008) (National Bureau of Statistics of China, 2003-2009), the net virtual water export is about 3.1% of the total water resources of the country. This is seemingly a small percentage. However, not all the water resources of the country are accessible because of geographical, topographical and other barriers. This is particularly the case for the abundant water resources in the southwest corner of the country, which is generally not accessible for other regions.

Looking into individual regions, the situation differs largely. In the HHH region (Huanghe-Huaihe-Haihe region), which is extremely water scarce, the net virtual water export is about 5.1 % of the water resources of the region. Nearly 8% of China's net virtual water export is from this region. Hence, the impact of China's international trade on its water resources is much more significant when reviewed at the regional level.

According to the Chinese statistics, the total water use in China is 550×109 m^3/year (National Bureau of Statistics of China, 2003-2009). The net virtual water export of 68.2×109 m^3/year accounts for 11.5% of the total water use. In other words, 11.5% of the water use in China is for the production of goods and services for export. For individual provinces, variations are significant. It is noticeable that some water scarce provinces, such as Tianjin, Shanghai, Shandong, have large shares. In Tianjin, an extremely water scarce area with the water resources of 106 m^3/capita (National Bureau of Statistics of China, 2008), 27% of the water use is 'exported' in the form of virtual water. In Shanghai and Shandong, the shares are 18% and 16%, respectively. Hence, the virtual water export in these provinces has significant impact on their water resources. With strong export-driving growth mode, it is expected that water demand will continue to increase, putting further pressure on their already stressed water resources.

The net virtual water exports were highly concentrated in 14-ETE, 5-CLT and 4-TXG, which are typically labour intensive, employing a large number of rural migrant workers. In terms of water use, 5-CLT and 4-TXG are rather water intensive sectors with high TWUC in their whole production chains. The share of these sectors is often high in water scarce regions, such as Tianjin, Hebei and Shandong. The impact of the international trade on water resources in the water scarce provinces is therefore more significant.

In addition to the impact on water resources in quantity, China's international trade also poses impact on its water quality. The wastewater discharge from 3-FTP, 4-TXG, 5-CLT and 7-PAP accounts for a large percentage in the total industrial wastewater discharge (Wang et al., 2008). The small scale and low technology rural enterprises are mostly concentrated in these sectors. Hence, China is exporting a large amount of virtual water to other countries while keeping heavy water pollution to itself.

Table 3. Net virtual water export (NVWE) & water resources (WR) in different regions (2007)

Regions	Provinces	2007			
		WR/cap	NVWE	NVWE / WR	NVWE / WU
		m^3/capita	$10^6 m^3$	(%)	(%)
North (the HHH region)	Beijing Tianjin Hebei Shanxi Shandong Henan	331	5240	5.1	6.9
Northeast	Liaoning Jilin Heilongjiang	1196	378	0.3	0.7
East and Middle	Shanghai Jiangsu Zhejiang Anhui Jiangxi Hubei Hunan	1696	21662	3.5	10.8
South	Fujian Guangdong Hainan Guangxi	2977	26044	5.2	25.7
Southwest	Chongqing Sichuan Guizhou Yunnan	2979	423	0.1	0.8
Northwest	Inner Mongolia Shaanxi Gansu Qinghai Ningxia Xinjiang	2198	14429	5.6	14.2
	Nation	1737	68177	3.1	11.5

(Data source for WR/cap: China Statistical yearbook 2003-2009)

Source: Zhang et al., 2011a.

Conclusion

This study systematically analyses the virtual water flows associated with international trade in China. The results show that China is a net virtual water exporter of 68.2×109 m^3/year, accounting for 3.1% of its renewable total water resources and 11.5% of the total water use. The impact of China's international trade on its water resources is much more significant when reviewed at the regional level. Water scarce provinces, particularly those in the HHH region, tend to have higher ratios of virtual water export to their water resources and water uses. For individual sectors, major net virtual water exporters are those where agriculture provides raw materials in the initial process of the production chain. The results suggest that China's economic gains from being the world 'manufacturing factory' have been attained at a high cost to its water resources.

It should be pointed out that a country's or region's international trade occurs for multiple reasons, including economic development, political motivation, social consideration, historical trend, natural endowments (apart from water), technology, etc., rather than the water resources concern only. Even for the water sufficient regions, it is imprudent to claim that virtual water export is laudable because of the needs to consider trade-offs between the economic well-being and the state of the environment. The results from this study indicate that it is important to incorporate international virtual water trade into the strategic water and trade planning in China, particularly for the regions with severe water scarcity.

This study provides a sectoral-based investigation into the virtual water flows associated with China's international trade with regional specifications. One improvement for future study would be to apply an agriculture sector-subdivided input-output table, and to incorporate the potential social/environmental impact into virtual water assessment.

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3. CWUModel: A water balance model to estimate the water footprint in the Duero river basin

Ángel de Miguel, Malaak Kallache, Eloy García-Calvo
IMDEA Water foundation, c/ punto net, edificio Zye, 2º Planta, Alcalá de Henares, 28805, Spain

Abstract

The aim of this paper is to present a crop water use model (CWUModel), which has been used to compute the Water Footprint (WF) of cereals in the Duero river basin in Spain. This model allows for the determination of daily water balances in a geospatial context, distinguishing between green and blue water requirements of crops. Because the soil plays a key role in simulating the water balance, three different criteria of water capacity of the soil were used. Cereal water consumption in the Duero basin is 4,984 million cubic meters per year (Mm^3/yr), of which 89% of the water corresponds to green water and 11% to blue water. Barley is the main consumer of water in the basin, with 2,410 Mm^3/yr, followed by wheat with 1,612 Mm^3/yr. Oat is the main consumer per unit of product, 1,501 m^3/ton (94% green, 6% blue), while maize is the main consumer of blue water, 668 m^3/ton (38 % green, 62% blue). The total WF is very similar in all three scenarios, with a variation less than 6%. Nevertheless, these differences increase when comparing the type of water, reaching differences of 17% for blue water, and 8% in the case of green water. The study shows that the CWUModel is a useful tool to estimate the water requirements of crops at regional level, because the use of local information as input in the water balance. Future studies will be focus on the calculation the overall water footprint of the Duero river basin, including the grey water footprint in the analysis.

Introduction

Worldwide, agriculture accounts for over 70% of blue water consumption (FAO, 2011). The anticipated future increase in global population, from 6.9 billion people in 2010 to 9.3 billion by 2050 (UN, 2010), entails the increase of agricultural production. It is estimated that by 2030 50% more food has to be produced, and twice the current amount of food by 2050. However, this increase in food production should be carried out with the least amount of water needed, mainly due to increases in urban and industrial water consumption and possible consequences of climate change (Parris, 2010). According to Holden (2007), it will be necessary to increase the water needed for food production from the current 7.000 km^3 to 9.000-11.000 km^3 by 2050.

Spain is no exception, water consumption is strongly geared towards the agricultural sector (INE, 2008), and the rate of exploitation of renewable resources exceeds 30% (EUROSTAT, 2011). In the past 20 years, the irrigated area has raised to 20% (MARM, 2010), causing a large increase in water demand. This makes Spain the country with the largest irrigated area in Europe, with nearly one third of the total European irrigated area (Lopez-Gunn et al., 2012). Nevertheless, Spain remains a net importer of virtual water, with more than 25,000 million m^3 per year, mainly associated with the import of cereals and industrial crops such as soybeans or cotton (Garrido et al., 2010). But more and more criticism arises against the agriculture sector remaining the centre stage (Lopez-Gunn et al., 2012). The old paradigm “more crops and jobs per drop” is shifting towards “more cash and nature per drop" (Aldaya et al., 2010). Determining the current and future water demands will help to implement sustainable policies for water resources management.

Water use at a national level has traditionally been measured by indicators such as water withdrawal, which only considers the total freshwater used by a country in its production system. The use of indicators such as the Water Footprint (WF) allows us to analyse not only the impacts generated at the national level, but all those associated with the consumption of goods produced abroad (Hoekstra and Chapagain, 2008). This multidimensional indicator distinguishes also between blue water (surface and groundwater) and green water (water from rain accumulated in the soil). It is furthermore possible to quantify the impact of pollution by calculating the gray water, which is defined as the total freshwater required to assimilate the load of pollution (Hoekstra et al., 2011).

The Virtual Water (VW) concept was defined by prof. Tony Allan in the beginning of the 90´s (Allan, 1993; 1994). Since then, notable advances in the development of the Water Footprint concept have been achieved. The first major quantification of water flows associated with trade of commodities was made by Chapagain and Hoekstra (2003; 2004). They established the VW flows of several crops and derived products. Nowadays, this methodology is standard, thanks to the efforts of the researchers of the Water Footprint Network (Hoekstra et al., 2011). Methodological advances include the use of complex geographical models to estimate the water use of crops (CWU). These models are based on water balances equations. They allow for the estimation of the amount of water embedded in crops in a certain area and at a given time.

Water balance models can be developed at different time and spatial scales, thus they vary in complexity and input data (Xu and Singh, 1998). There are several models to calculate crop water requirements on a global scale. Some of the most recent ones have been implemented by Siebert and Döll (2010), with a resolution of 5 minutes and a total of 26 crop classes (both for rainfed and irrigated conditions). The model developed by Mekonnen et al. (2010), with the same spatial resolution was applied to 126 crops, including calculations of gray water. Liu et al. (2009; 2010) developed a model to estimate the crop water use with a 30 minutes resolution. The certainty of these models is strongly influenced by the input data: location of crops and planting dates, weather variables, soil properties, etc. (Siebert and Dôll, 2010). The total available water capacity of the soil (TAWC) plays a critical role in determining the overall water balance (Ji et al., 2009), because it acts as a water reservoir.

The aim of this paper is to present a crop water use model (CWUModel), which computes the Water Footprint of agriculture in the Duero river basin. This model enables daily water balances in a geospatial context, distinguishing between green water and blue water. The main differences between CWUModel and models mentioned above are:

- working resolution is 1 km, compared to the 5 minutes (about 8 km at Spanish latitude) resolution of some of the global scale models;
- the model has been generated by the tool Model Builder (ESRI ArcGIS 9.3) and subsequently exported to Python, therefore it does not require extensive knowledge in programming languages;

- daily weather data has been used. The data were obtained from monthly data. We generated daily precipitation amounts by means of a stochastic weather generator, which has been calibrated to the basin conditions beforehand, and;
- we built a crop location map merging statistical information with the land use map.

Here, we present the first results obtained with the CWUModel. We calculated the WF of cereals in the Duero basin for 2001-2008, distinguishing between green water and blue water. Since soil is a key element in the water balance, we performed an analysis of 3 scenarios with different TAWC amounts.

This article lays the basis of a future detailed study on Water Footprint of agriculture in the Duero basin, including all crops to be found in the river basin, and water flows associated with the exchange of goods. An analysis of grey water footprint will be included too.

The paper is structured as follows: (i) the first part shows the methodology used to develop the CWUModel: the CWUModel structure, the daily precipitation generator and the crop location maps (ii) the second part shows the main results: the daily precipitation series, the crop areas and the main results of the WF of cereals in Duero river basin.

The Duero basin, the study area, is the largest river basin of the Iberian Peninsula, covering 98,073 km^2 along the westwards course of the Duero River and its tributaries (Figure 1). The river basin occupies mostly Spanish territory (80%, 78,859 km^2) but a significant 20% (19,214 km^2) is situated in Portugal. Climatically the basin has a continental Mediterranean climate, with an average annual rainfall of 612 mm. There are, however, significant climatic differences within the river basin. Average precipitation, for instance, spans from ca. 1,800 mm in the peripheral mountain ranges to less than 400 mm in continental areas of Castile and Leon (DHC, 2010). From a water management point of view, the sub basins are grouped into 13 Water Management Units (WMU) (Figure 1).

Land use of the basin is mainly agricultural, 42% of the territory being occupied by farmland (EEA, 2005). Most crop areas are rain-fed (ca. 3,5 million ha), while irrigated production occupies ca. 480,000 ha. Most land is used for cereal production (64% of the total arable land, 84% in rain-fed and 14% in irrigation systems), mainly barley, maize, oats and wheat. The annual production of grain and straw constitute respectively 24% and 21% of the total Spanish production. However, the Gross Added Value (GAV) of agriculture is as low as 7% employing less than 11% of the total population of the area.

The hydrologic resources of the basin are mainly used in agriculture, ca. 4,500 Mm^3 of blue water of the total of 5,000 Mm^3 used in the basin (DHC, 2010).

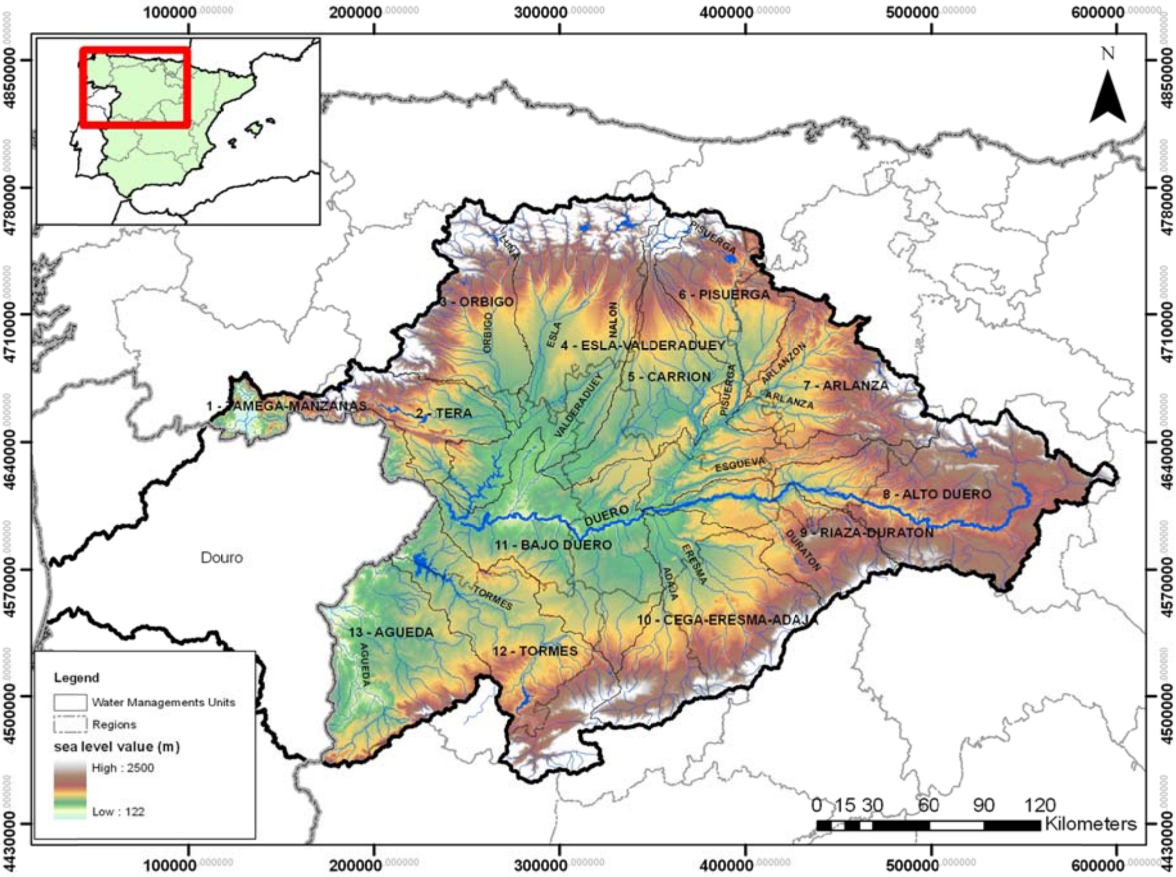

Figure 1. Spanish part of Douro River basin

Method and data

Model structure

The CWUModel is a spatially-explicit water balance model to estimate the water used by crops. The model is based in the work of Mekonnen et al. (2010; 2011), and Siebert and Döll (2010), which estimate the actual evapotranspiration (ET_a) of the crop in non-optimal conditions (Allen et al., 1998). Water balance was calculated with a daily time step based on particular crop and soil features as well as the main climatic variables. Calculations were done at a fine spatial scale (1 km) and using a hydrological year (October-September) which is coherent with the climate of the basin (Custodio and Llamas, 1983). Python scripts were built in Model Builder (ESRI ArcGIS 9.3). For all calculations, the value of adjacent cells is computed independent by using a grid model. The potential water flow between neighbouring cells has not been considered. The water balance for each crop type and time step is determined by the following expression:

$$P + I = ET_a + R + \Delta S \tag{1}$$

P is the precipitation (mm), I is the water input by irrigation (mm), R is runoff water (mm). Actual evapotranspiration (ET_a) is a function of the crop evapotranspiration (ET_c):

$$ET_c = K_c \cdot K_s \cdot ET_o \tag{2}$$

where ET_o is the reference evapotranspiration, K_c is the crop coefficient and K_s is the water stress coefficient. K_c is specific for each crop, varying along the time. The parameters needed to estimate the daily K_c are obtained from Allen et al. (1998). Daily K_c is computing by linear interpolation between the initial values of K_c at the different crops stages (initial, developing, mid and late season) using the number of days a crop is in each season. K_s is introduced to account for water stress conditions. It indicates the energy required to uptake water (water potential energy). K_s is crop specific and defined as

$$K_s = \begin{cases} \dfrac{S[t]}{(1-p)\cdot S_{\max}}, if\ S[t] < (1-p)\cdot S_{\max} \\ 1 \end{cases} \tag{3}$$

where for each time period t, S is the soil moisture, and S_{max} is the maximum moisture a soil can hold. S_{max} is a function of the TAWC of a soil and the respective root depth. The crop specific depletion factor (p) refers to the amount of water, a crop type can extract from the soil without suffering water stress. We simplified the model by using a constant value of p for all the vegetative periods of each crop (Allen et al., 1998). K_s values are computed according to Allen et al. (1998). Furthermore, different root depth values were used for rainfed and irrigated crops (USDA, 1997).

TAWC grid-based data at 1 km resolution were taken from ESDB database (Panagos et al., 2012). Two horizons are identified: deep and superficial (up to 15 cm deep). S_{max} was calculated by multiplying TAWC values with the crop's root depth. In case the root depth had a higher value than the maximum soil depth, the last was used to calculate S_{max}. The information provided by ESDB establishes several ranges of TAWC, depending on soil hydraulic properties (Figure 2). To determine the influence of this variable on the water demands of crops, the model has been run in 3 different scenarios. The first one selecting the lowest values (*Low*) of each range of TAWC at a grid cell, the second the mean values (*Medium*) and the third scenario the highest ones (*High*).

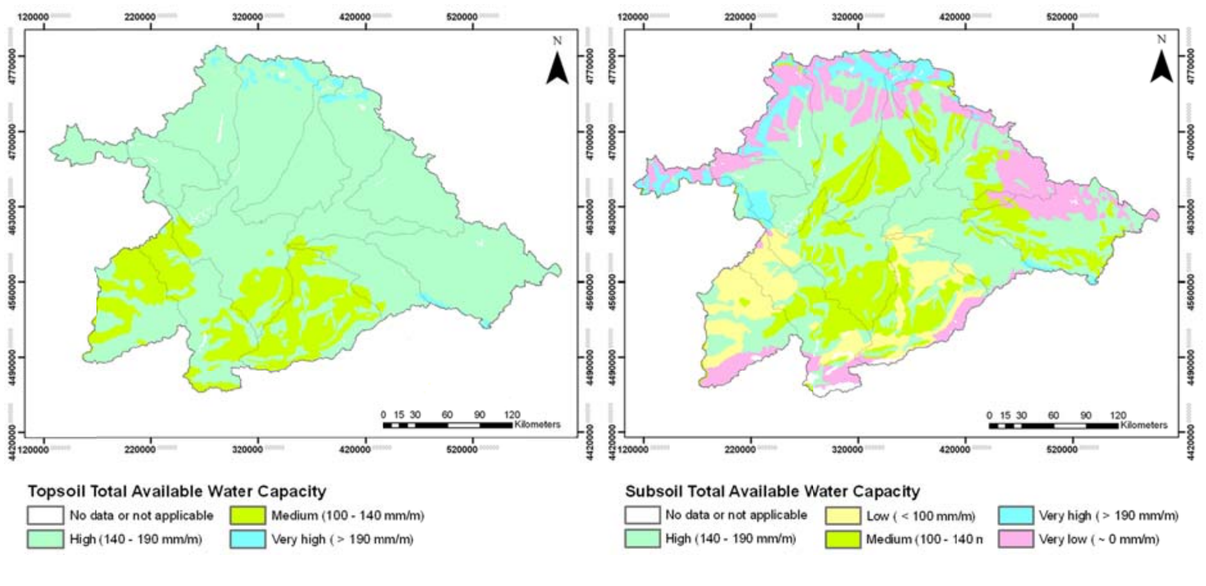

Figure 2. Total available water capacity of soils in Duero River Basin. Maps provide by ESDB database (Panagos et al., 2012). Left figure represent the TAWC of topsoil (15 cm depth). Right figure represents the TAWC of subsoil.

Monthly ET_o and P were obtained from the dynamical model SIMPA (Álvarez et al., 2005), which offers monthly climatic information with a 1 km average over the period 1940–2010. In SIMPA, ET_o is obtained by combining the Thornthwaite and Penman-Monteith methods (Estrela et al., 1999). Monthly ET_o was rescaled to daily estimates of $ET_o(t)$ by means of linear interpolation. Monthly precipitation was downscaled to daily precipitation by using a stochastic weather generator (see section 2.2). Daily measurements of runoff (R) was computed as Lieden and Harlin (2000), see equation (4):

$$R = (P + I) \cdot \left(\frac{S}{S_{\max}} \right)^{\gamma_r} \tag{4}$$

Here I is irrigation water, S is soil moisture and S_{max} its maximum. The parameter γ_r is correlated with the runoff intensity. We used a fixed value of 2 for rainfed cultures and 3 for irrigation cultures following Siebert and Döll (2010).

The water balance is carried out independently for irrigated crops and rainfed ones. Rainfed crop water consumption corresponds exclusively to precipitation, which is green water. Meanwhile, irrigated crops are supplied by both systems: precipitation (green water) and irrigation (blue water). The irrigation requirements were calculated following the two balance methods proposed by Hoekstra et al. (2011). The first balance models crops without irrigation (here rainfed conditions prevail), and the second models fully irrigated crops. The difference between the crop requirements are assumed to be equal to the irrigation necessities, that is the amount of blue water. The water balances are computed for the whole year. A constant K_c of 0,3 before the planting date is used in order to define initial soil moisture. CWU is determined as the sum between green water and blue water requirements, neglecting the evapotranspiration outside the growing period.

WF of a specific crop was calculated according the proposal made by Hoekstra et al. (2011). Here the green and blue water footprints are calculated by dividing the crop water use by the actual yield of this crop. In our approach, the WF is calculated for each grid cell separately using the CWU. Information on production and yields of each crop was extracted from the statistical yearbook (MARM, 2010). The cropping season was obtained from the planting and harvesting calendar of the Ministry of Agriculture of Spain (MAPYA, 2002).

Generating daily precipitation

For the calculation of a daily water balance, daily climatic data is needed as input. For the area studied, daily observation series of climatic data were not available in the spatial resolution needed for our analysis. The observations were also too scarce to consider the spatial interpolation of the series (Liu et al., 2011), which is in any case doubtable given the high spatial variability of daily precipitation (Carrera-Hernández and Gaskin, 2007). We therefore derived these series from simulated monthly data. Daily weather simulators are the most common way to generate daily data and to thus circumvent the problems related to missing data (Wilks and Wilby, 1999). Stochastic weather generators are statistical models, based on random numbers. They resemble the observed data to which they have been fitted (Wilks, 1999). Although there exist different global data sets, which comprise the information needed for the generation of daily climatic data (New et al., 2002), their spatial resolution is usually too large to apply them directly in specific areas. Therefore we calibrated the stochastic weather generator with the available 41 series of daily precipitation observations in the Duero basin and data from 2000 to 2011. The stochastic daily generator we developed is based on studies by Castelví et al. (2004) and Schould and Abbaspour (2007). The stochastic model generates daily precipitation from monthly precipitation data of the dynamical model SIMPA. The model outputs are available for grid cells of size of 1 km. A first order Markov chain was used to describe the occurrence of precipitation. The procedure relies on the spatial transferability of link functions between the monthly precipitation amount and the frequency of wet days in a month, the transition probabilities from a dry day to a wet day and from a wet day to a wet day, and the parameters of a Gamma distribution (which is assumed to represent well the daily precipitation on wet days). Here a “wet day” is defined as day with equal or more than 0.1mm precipitation, which is a standard definition.

Growing areas

It is essential to know the location of a crop in order to estimate its WF. Therefore, we built a map of the growing area of each cereal. This map is based on the "Occupation of Land Information System in Spain" (SIOSE) of the Geographical Institute of Spain (IGN, 2011) and provides information on land use in 2005. It has a scale of 1:25.000 and disaggregates land use in over 90 categories, of which 12 belong to arable areas. Each category contains attributes based on the management system (rainfed, irrigation and greenhouse). We have chosen SIOSE instead of similar covers, such as Corine Land Cover (EEA, 2005) due to its better spatial resolution, disaggregation of the crop groups and ease of reference. It is necessary to know the exact location of each crop in order to calculate the CWU. Therefore the map has been combined with statistical information. We used two databases with different spatial and temporal resolution. First, we used the statistical yearbook of Spain (MARM, 2010), that provides annual information on arable land at a provincial level (there are 11 provinces in the Duero basin) for over 80 crops. To improve the spatial resolution, this data has been combined with the agricultural census (INE, 2012), that provides information on 12 groups of crops at a regional level (there are 57 counties in the basin) for every 10 years. Fallow lands were removed based on to the statistical information. We considered that each pixel belonging to a crop group is composed proportionately of all those crops listed in the statistical information. This makes it possible to generate a specific map for each crop. Although this paper was focused on 2001-2008 average, the use of yearly statistical information provides the capacity to create yearly crop maps and so varying yearly the proportion of grid cell assigned to each crop (Figure 3).

Results

Verification of the generated daily precipitation

In Figure 4, a comparison between a SIMPA map and the map of the monthly sum of precipitation generated by the weather generator are depicted for month March, 2006. Furthermore, the values obtained by the precipitation generator and the monthly SIMPA values were compared via the correlation coefficient. Correlation between raw cell values is over 92%, and the correlation between average values per WMU used, increases even to 99,9%. Since all parameters of the stochastic model depend on the monthly precipitation amount, a potential trend in precipitation in the SIMPA data will transfer to the generated daily precipitation. This concerns frequency as well as the amount of precipitation.

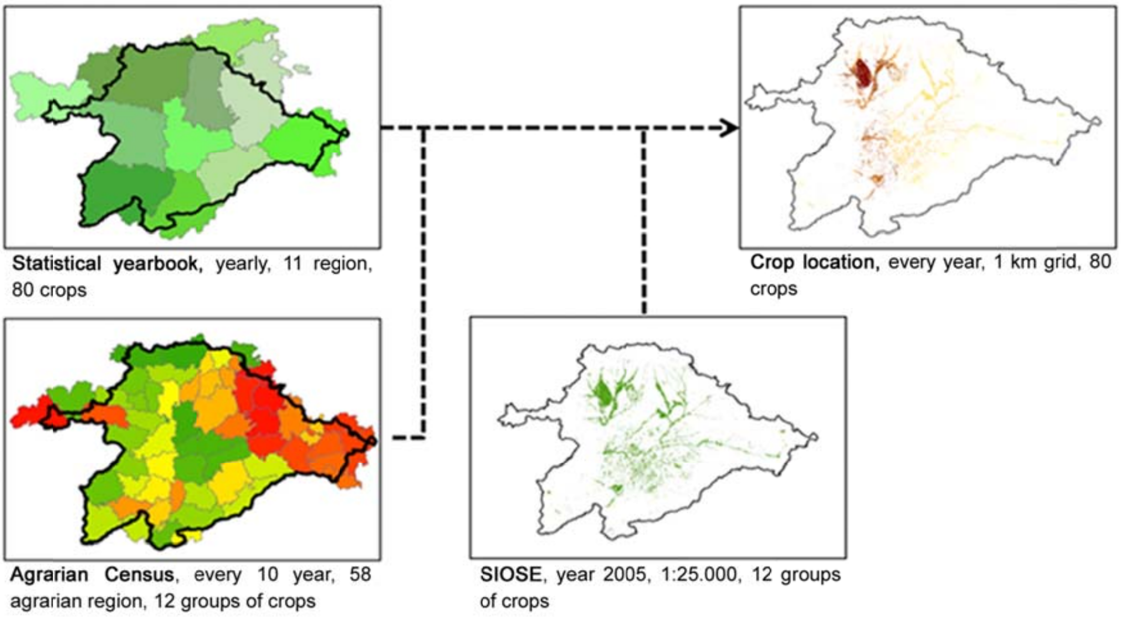

Figure 3. Steps to transform the SIOSE map into a yearly crop location map using statistical information.

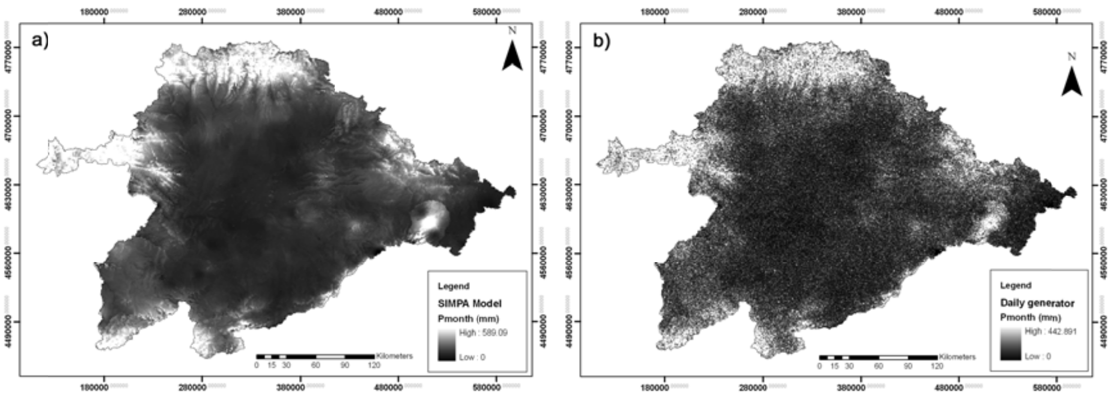

Figure 4. a) Precipitation in March provides by SIMPA. b) Sum of daily precipitation in March generated by Stoksastic model

Growing areas

We generated a crop location map by combining statistical information and the land use map (SIOSE), which shows the cereal distribution in the Duero basin. SIOSE only contains major crop groups, while statistical information adds information at an administrative level. We were able to build a distribution map for each crop by using both sources of information. By means of these maps, we can reconstruct the used agricultural area for each year (leaving aside the fallow land). As seen in Table 1, the total usable area of cereals in the Duero basin for the period 2001-2008 is nearly 1.9 million ha, of which 85% belong to areas with rainfed cereals (here barley and wheat are the most representative cereals). Irrigated cereals occupy nearly 280,000 ha, of which maize and barley occupy about 100,000 ha each. The total agricultural area of the basin is about 3.5 million ha, and cereals occupy 56%. Rainfed cereals are responsible for 57% of the total rainfed areas, while irrigated cereals are responsible for 50% of the surface equipped with irrigation infrastructures.

Table 1. Cereal surface in Duero River Basin in hectares, and percentage of the total agrarian surface in each system (AS). Average 2001-2008 period

	Rain-fed						Irrigated					
Subzone	Wheat (ha)	Barley (ha)	Oat (ha)	Maize (ha)	Total (ha)	% $AS_{rainfed}$	Wheat (ha)	Barley (ha)	Oat (ha)	Maize (ha)	Total (ha)	% $AS_{irrigated}$
1. Támega-Manzanas	1,775	792	229	295	3,091	31	0	0	0	0	0	0
2. Tera	3,513	5,696	1,655	3	10,868	35	519	1,466	161	2,659	4,806	46
3. Órbigo	4,480	4,739	4,083	1	13,304	29	6,804	4,996	3,165	36,483	51,448	58
4. Esla-Valderaduey	37,352	81,462	25,835	17	144,666	41	5,807	7,025	2,538	29,880	45,249	47
5. Carrión	42,233	127,923	14,467	6	184,628	58	9,609	13,899	1,124	5,203	29,835	48
6. Pisuerga	75,335	158,869	12,492	91	246,786	67	5,861	10,380	603	3,320	20,164	45
7. Arlanza	77,685	97,636	4,195	70	179,585	70	1,475	2,353	93	434	4,355	44
8. Alto Duero	78,622	111,774	1,525	31	191,952	59	3,780	7,798	77	732	12,386	51
9. Riaza-Duratón	23,376	81,396	1,634	10	106,416	63	1,445	6,353	90	1,529	9,417	47
10. Cega-Eresma-Adaja	42,810	141,713	3,902	30	188,454	65	2,131	14,296	304	2,116	18,847	45
11. Bajo Duero	56,227	182,581	21,158	43	260,009	56	6,446	31,827	1,463	22,086	61,822	52
12. Tormes	32,221	48,959	15,011	13	96,203	52	2,066	4,371	991	10,862	18,291	53
13. Águeda	10,551	14,431	5,089	3	30,074	38	118	242	58	624	1,042	22
Total surface	486,178	1,057,970	111,274	612	1,656,035	57	46,060	105,007	10,667	115,928	277,661	50

Crop water use

We used CWUModel to estimate the WF of cereals in the Duero basin for 2001-2008. Since the model has been run in three different scenarios, which depend on the water holding capacity of the soil, we used the average values of the three scenarios in the analysis of the results.

We established the WF of cereals in the Duero basin as 4,984 Mm^3/yr for the period 2001-2008, of which 89% correspond to water from rain (green water) and the remaining 11% to irrigation (blue water). Rainfed lands are responsible for 76% of the total water consumption (with 3,822 Mm^3/yr), whereas irrigation needs are established in 1,162 Mm^3/yr. The main water consumer is barley, with 2,410 Mm^3/yr, followed by wheat with almost 1.612 Mm^3/yr. Water consumption by oat and maize is much lower with 364 and 598 Mm^3/yr. Regarding the water sources, we find that maize is the main consumer of blue water (with almost 64% of the total amount of blue water consumed by cereals, which is 350 Mm^3/yr), compared to 80, 70 and 37 Mm^3/yr consumed by wheat, barley and oat, respectively. Figure 5 shows the weight that each crop has on the WF of cereals in the basin.

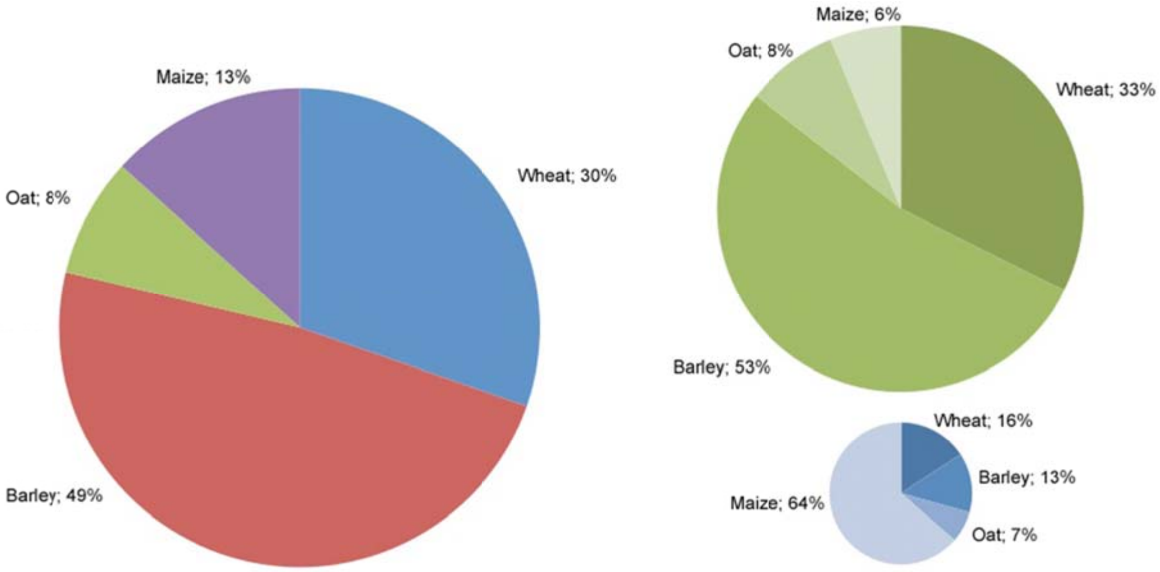

Figure 5. Contribution to the water footprints of cereals in Duero water basin. Left cake plot refers to the total water footprints, green and blue cake plot refer to the green and blue water footprint

As shown in Table 2, oat is the crop with a higher WF per ton of crop, 1,501 m^3/ton (94% green water, 6% blue water), followed by wheat, with 967 m^3/ton (96% green water, 4% blue water), barley with 756 m^3/ton (98% green water, 2% blue water) and maize with a total WF of 668 m^3/ton (38% green water, 62% blue water). The total WF show some difference related to the management system used. Water consumption on irrigated land is higher for wheat and oat (3% and 16% respectively). In case of barley and maize, rainfed lands show a higher water demand (18% and 6% respectively) than the respective irrigated lands.

Table 2. WF per ton of cereals in Duero river basin

	(m^3/ton)	Wheat	Barley	Oat	Maize
	WF green	965	770	1,479	713
Rainfed	WF blue	-	-	-	-
	WF total	965	770	1,479	713
	WF green	579	468	694	248
Irrigated	WF blue	417	158	1,065	421
	WF total	996	625	1,759	669
	WF green	932	742	1,417	251
Weighted Average	WF blue	35	14	84	417
	WF total	967	756	1,501	668

When looking at the geographical distribution, we find that the WF is well distributed throughout the basin (Figure 6). The average consumption is about 2,637 m^3/ha, although there are large differences among rainfed and irrigated areas. While rainfed agriculture has an average consumption of 2,315 m^3/ha of green water, irrigated agriculture has a much higher consumption, 4,322 m^3/ha, of which 53% corresponds to blue water and the other 47% to green water. This effect can be clearly seen in Figure 6. The darker areas are those with a more intensive water use, corresponding to crops in the irrigation system. In some specific areas water needs reach up to 6.200 m^3/ha.

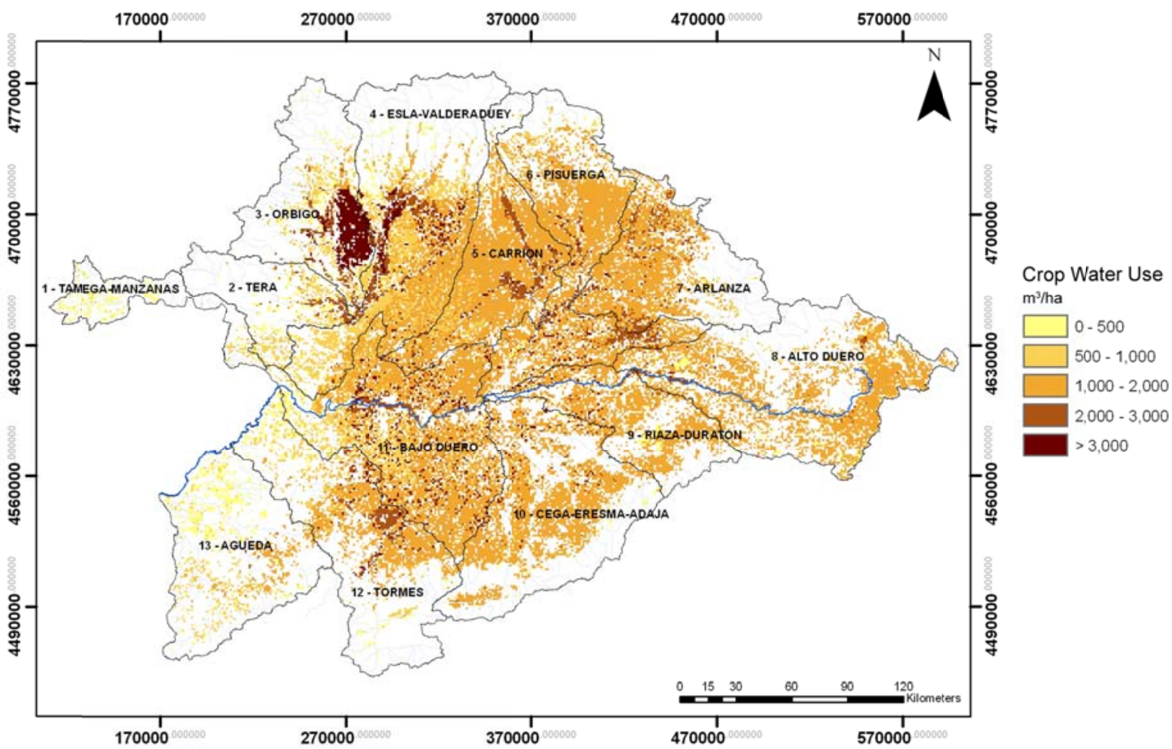

Figure 6. Green and blue water footprints of cereals in Duero river basin. Data are shown in m^3/ha.

The water management unit (WMU) with the largest WF is Bajo Duero, with 796 Mm^3/yr, followed by Pisuerga, Esla-Valderaduey and Carrión with 650, 557 y 531 Mm^3/yr respectively (Figure 7). Most of the water used corresponds to green water – in some units such as Arlanza, Alto Duero or Águeda this corresponds to more than

95% of the total water-. But some units have high blue water consumption - as Órbigo with 139 Mm^3/yr, which is nearly 50% of the total consumption. Esla-Valderaduey and Bajo Duero with 112 y 102 Mm^3/yr are important blue water consumers too. Maize is the crop responsible for the high water consumption in these units, accounting with 79, 78 and 63% respectively.

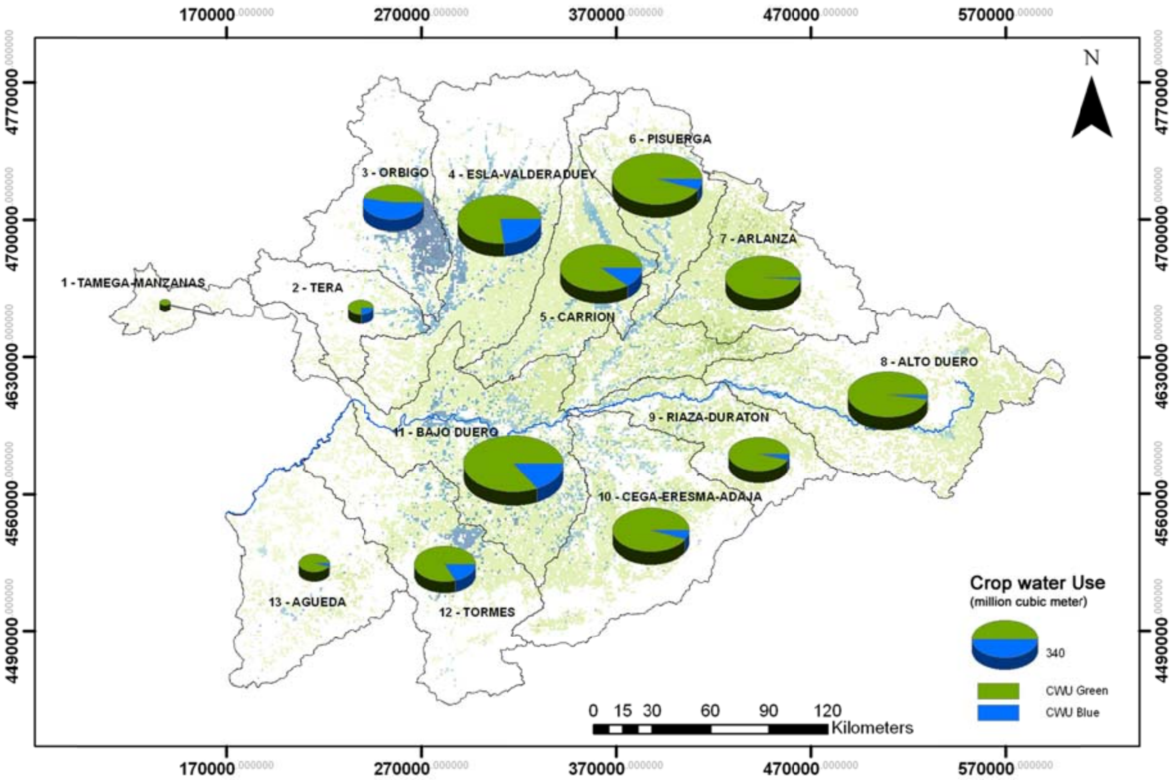

Figure 7. Total, green and blue water footprints of cereals in different water managements units of Duero river basin, in Mm^3.

Figure 8 shows the temporal distribution of WF throughout the year. The pattern changes depending on the importance of the irrigated crops. Figure 8 a) corresponds to the value of the entire basin, where green water is the main source. The highest levels are reached in March, April and May, when potential evapotranspiration (PET) levels are not yet at their maximum, and the amount of water stored in the soil is still high. Blue water demand starts in April, being more important in May, June, July and August. These months are characterised by high PET and low precipitation rate. Figure 8 b) shows the Alto Duero unit, where green water consumption is predominant (due to a lack of irrigated cereals, which are less than 13,000 ha compared to 190,000 ha of the rain-fed). Támega-Manzanas, Pisuerga, Arlanza, Riaza-Duratón, Cega-Eresma-Adaja, and Águeda units follow the same pattern. Figures 8 c) and d) correspond to the Carrión and Elsa-Valderaduey units, respectively. In the first unit, the highest consumption is in summer (June, July and August). This is due to its dominant crop sort, which is maize, planted from late April to May. Blue water consumption is quite high, mainly in the last months of the hydrological year, when evapotranspiration is very high and water storage is limited. Water consumption in the second unit is produced in spring and early summer. Here a high presence of wheat and barley is given, which growing season ends in July. From June on, blue water consumption is predominant and corresponds almost exclusively with maize.

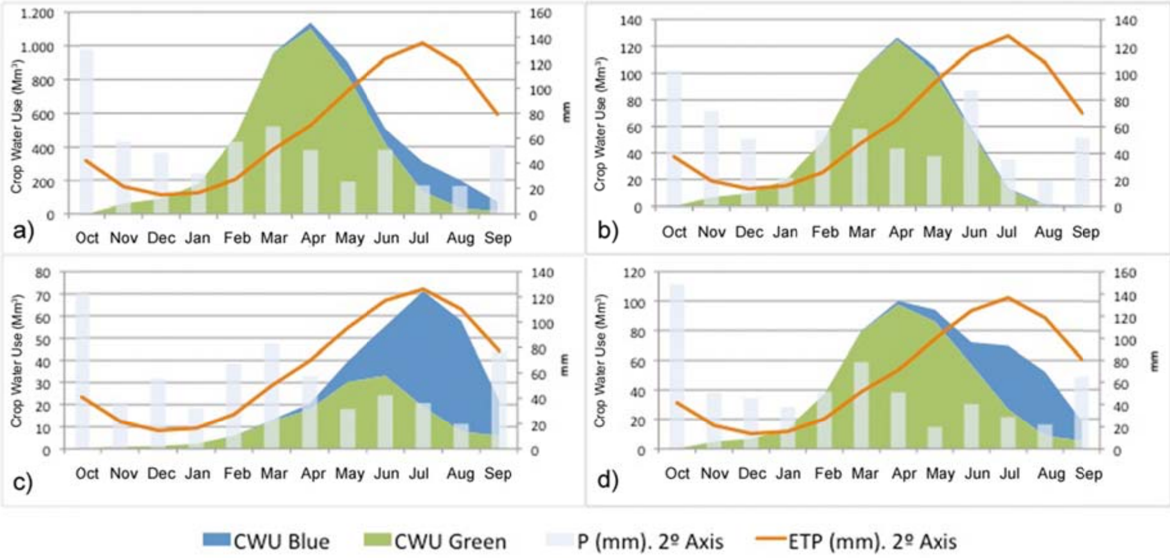

Figure 8. Water footprints in Duero river basin throughout the year, in Mm^3; a) Duero river basin; b) Alto Duero; c) Órbigo; d) Esla-Valderaduey

Influence of soil in the water balance

Water retention capacity of the soil is a key parameter in the water balance: The soil is the reservoir where the water is stored, which is later used by crops. Edaphologic data at finer scales are often not available Thus, for this project we used the coarser European Soil Data Base (Panagos et al., 2012), which provides information on soil types and physical and chemical characteristics at a 1:1,000,000 scale. Given the hydraulic properties provided, TAWC (mm/m) is the main hydraulic property variable for soils, distinguishing between two edaphic horizons: superficial and deep. For accuracy at a coarse scale, the variability in hydraulic parameters around the average is presented as a range. To assess the influence of this parameter on water balance and water use estimates, the model was run using the low, average and high values of the range as separate criteria.

In Table 3 we present the estimates of WF of cereals in the Duero River basin as a function of the three proposed scenarios. The results are presented for each of the WMU found in the basin. Total WF is similar in the three scenarios, ranging between 4,865 Mm^3/yr and 5,084 Mm^3/yr for low and high respectively, which implies a deviation of 6%. If we focus on water source, the differences are higher. In the high scenario, blue water demand is lower (501 Mm^3) than in the *low* one (605 Mm^3), which means ca. 17% of difference. Green water demand in the *high* scenario (4,583 Mm^3/yr) is 8% higher than in the *low* (4,260 Mm^3). Related to the management system, difference in rainfed cops reach 7% (3,678 in *low* versus 3,936 Mm^3 in the *high* scenario), while deviation in irrigated farms is lower than 3%. The green/blue ratio is also affected by TAWC, reaching from 56% in the *High* scenario to 49% in the *Low*. This is because the reduction of green water consumption for the *low* scenarios – less water available in the soil-, is compensated with an increase in the irrigation water demand.

Discussion

The study by Mekonnen et al. (2011) reported that the WF for the Douro river basin is 13,943 Mm^3/yr (87% green and 13% blue). In the case of cereal crops (wheat, barley, oat and maize) the total WF is 7,024 Mm^3 (88%

green and 12% blue). These values relate to the whole basin –Spain and Portugal-, therefore they cannot be compared directly.

Table 3. Green and Blue water footprint of cereals in Duero river basin related to 3 different scenarios of total available water capacity obtained by ESDB (thousand m^3).

Water Management Unit (WMU)	WF (m^3)	*Low*		*Medium*		*High*	
		Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
1. Támega – Manzanas	WF green	8.275	0	8.527	0	8.630	0
	WF blue	-	0	-	0	-	0
2. Tera	WF green	28.443	9.990	29.484	10.694	30.305	11.328
	WF blue	-	12.492	-	10.926	-	10.250
3. Órbigo	WF green	30.850	105.576	32.204	113.487	31.984	117.776
	WF blue	-	153.066	-	136.888	-	128.535
4. Esla – Valderaduey	WF green	323.755	99.694	341.422	107.026	349.768	112.894
	WF blue	-	125.451	-	109.395	-	103.320
5. Carrión	WF green	391.699	65.961	412.058	69.878	420.649	72.364
	WF blue	-	58.735	-	52.857	-	50.327
6. Pisuerga	WF green	554.226	44.583	578.053	47.124	588.365	48.964
	WF blue	-	33.471	-	29.780	-	27.939
7. Arlanza	WF green	431.191	10.013	447.369	10.549	452.297	10.885
	WF blue	-	5.380	-	4.692	-	4.355
8. Alto Duero	WF green	449.784	30.176	465.788	31.479	470.346	32.298
	WF blue	-	11.399	-	9.918	-	9.097
9. Riaza Duratón	WF green	252.012	21.034	261.758	22.143	268.590	23.026
	WF blue	-	11.154	-	9.558	-	8.668
10. Cega – Eresma – Adaja	WF green	395.662	36.344	416.855	38.527	431.125	39.883
	WF blue	-	24.537	-	21.606	-	20.244
11. Bajo Duero	WF green	540.047	121.224	568.863	129.271	587.075	135.549
	WF blue	-	114.876	-	99.706	-	93.274
12. Tormes	WF green	203.610	35.205	216.054	37.975	222.521	39.899
	WF blue	-	50.863	-	44.369	-	42.386
13. Águeda	WF green	68.991	1.870	73.058	2.027	74.732	2.103
	WF blue	-	3.363	-	3.065	-	2.984
Total	WF green	3.678.547	581.671	3.851.493	620.182	3.936.387	646.968
	WF blue	-	604.786	-	532.761	-	501.378
	CWU Total		**4.865**		**5,004**		**5,084**

In the case of wheat, Mekonnen reported a WF of 2,248 Mm^3/yr (97% green, 3% blue) versus 1,612 (96% green, 4% blue) obtained in this study. For barley the differences are higher: 3,290 Mm^3/yr (91% green, 9% blue) versus 2,410 (94% green, 6% blue). Maize has a total water consumption of 925 Mm^3/yr (48% green, 52% blue) in Mekonnen's study, versus 598 (38% green, 62% blue) in our study. Finally the WF of oats is reported as 297 Mm^3/yr (94% green, 6% blue) compared with 326 Mm^3/yr (94% green , 6% blue) found with the CWUModel. Other studies also provide information about the river basin. Rodriguez-Casado et al. (2008) found a total WF of 4,331 Mm^3 (50% green, 50% blue) for all crops in the river basin. Camarero et al. (2011) estimate the WF of the

Duero basin at municipal level, finding a total WF of 5,084 Mm^3. None of these studies are based on a spatially explicit water balance.

The CWUModel results have been compared with the WF per ton of crop proposed by Mekonnen and Hoekstra (2011) for cereals in the region of Castile and Leon (Table 4). The WF of the Mekonnen study is always higher, with a deviation of: wheat, 30%; barley, 26%; oat, 2%; maize, 4% (Table 4). The reduced scale of the CWUModel, which uses more local input values, suggests a fine quality of the estimations. However, as outlined by Mekonnen and Hoekstra (2010), the model outputs are sensitive to soil variables and the crop calendar. Siebert and Döll (2010) regard the TAWC and statistical information of yield to be the most important sources of uncertainty of the results. For the CWUModel, the most local values available have been used, which might reduce uncertainty.

Table 4. Comparison of WF of different cereals in Duero water basin in m^3/ton computed by CWUModel (CWUM) and by Mekonnen and Hoekstra (M&H) (2011) for Castile and Leon region.

		Wheat		Barley		Oat		Maize	
	(m^3/ton)	CWUM	M&H	CWUM	M&H	CWUM	M&H	CWUM	M&H
Weighted Average	WF green	932	1,357	742	1,357	1,417	1,441	251	352
	WF Blue	35	28	14	28	84	91	417	340
	WF Total	967	1,385	756	1,385	1,501	1,532	668	692
Deviation (%)		30		26		2		4	

The water consumption of a crop is scarcely influenced by water management (Hoff *et al.*, 2010). The use of irrigation water implies an increase of water consumption by crops, but at the same time the yield also rises. Siebert et *al.,* (2010) found on the contrary that irrigated crops have a virtual water consumption which is 15% lower than rain-fed crops. A similar result was found by Liu et al. (2007) using the GEPIC model. Here wheat exhibited lower water consumption in case it was managed in an irrigation system. Other models, like IMPACT (Rosegrant et al., 2008), reported a 10% higher water use of rain-fed crops in comparison to irrigated farming. In our study, the differences between the amounts of virtual water are slightly higher when comparing different management strategies, reaching 18% and 16% of deviation in case of barley and oat. A trend in the water use related to the management system is not found. Rain-fed water consumption was higher for some crops, such as wheat and oat, while lower for the others. The use of statistical yield instead of computed values as other authors could be the answer.

TAWC is essential to estimate the CWU, especially in case of irrigated crops. The total CWU in irrigated farming is almost the same for the different soil types, since water not provided by precipitation will be added with irrigation. The relation between green and blue water amounts is the component, which is most affected by the soil type, reaching up to 7% deviation. The use of high TAWC values could lead to an underestimation of the true needs of blue water.

These first results document the importance of green water in the production of cereals in the Duero Basin. Moreover, as reported by Aldaya et al. (2010), green water has a strategic value when looking at the international commodity trade. According to Hoff et al. (2010), the amount of green water used to produce food is about 4-5 times higher than the amount of blue water, at global scale. In the Duero river basin grain of about 7 million tons are produced in total (5.4 in rainfed areas, 1.6 in irrigated areas). This underlines the importance of green water in this area. Here not only the grain produced under rainfed conditions is to mention, but also irrigated grain. Cereals are no exception, other typical Spanish crops, as olive, has as well a great green component (Salmoral et al., 2011). That means, green water is an important component of the production chain, reducing the pressure on the water resources. However, rainfed crops are not free of environmental impacts. Gómez-Limón and Riesgo (2009) performed an eco-efficiency analysis of 171 rainfed farms located in the Duero river basin. They found that most of the farms did not manage their inputs efficiently. They applied more fertilizer and pesticides than needed for the crops, which resulted in a higher risk of water pollution. Moreover, rainfed yield is related to the amount of rainfall during the growing season. This results in a great production variability in Mediterranean climates, because they are characterized by erratic weather pattern (Diacono et al., 2012). During the study period, the cereal rainfed production oscillated around 35% from year to year, whereas irrigated production remained relatively constant. Thus, the use of additional water helps to mitigate the effects of dry periods, although green water has a great importance for the cereal production in the Duero river basin.

With an overwhelming reliance on surface water resources, the irrigated efficiency for cereals is around 55% (Gómez-Limóm, 2006). To provide the 550 Mm^3 of blue water demanded by cereals, the transfer of around 1,250 Mm^3 water from rivers and aquifers is needed. But thanks to the irrigation return flow and recharge, most of this water returns to rivers and aquifers, or is used by natural vegetation (Mateos et al., 1996). This decreases the pressure on local water resources.

As Gomez-Limon et al. (2009) reported, the new water-pricing policy required by the European Water Framework Directive (WFD), based in the cost recovery principle, could cause a reduction of blue water consumption. This is due to the predominance of extensive crops, with low profitability and heavy dependence on subsidies. Gallego-Ayala and Gómez-Limon (2011) examined some scenarios with different crop prices and subsidy policies. They find a common trend towards replacing irrigated for extensive or rainfed crops. However, this potential reduction of water use could be possibly cancelled out by an increase in crop water demand due to climate change. Small changes in the climatic conditions might cause an increase of 5 – 11% of potential evapotranspiration in the whole river basin (Moratiel et al., 2011).

Conclusion

The CWUModel has been developed to estimate the WF in the Duero river basin. Naturally the same methodology can be applied to any other river basin, at least within the Iberian peninsula. The CWUModel is designed for regional scale studies and works at a lower scale than other (global) models. However, as regional information is not always available, an adequate rescaling of the available data is necessary for obtaining an accurate model.

A detailed knowledge of crop variables such as its location, surface extension and the planting date is important to obtain solid results. Generating crop location maps based on land use maps and statistical information improves the precision of the results. Crop location maps make the model more dynamic, as they reflect annual fluctuations in crop surface and production, making it possible to account for temporal variation of the crop's water use.

The SIMPA model provides monthly estimates of climatic variables, which are ready to use in environmental modelling, and important in the calculation of the hydraulic balance. Daily data can be generated by rescaling the model outputs by means of linear interpolation (i.e. PET) or by means of stochastic models. This last approach, used in the generation of randomized daily precipitation series, is a useful tool to generate serial data in case interpolation does not lead to adequate results. The use of (rescaled) model outputs is a way to circumvent the problem of missing observations (New et al., 2002). The rescaling of the monthly data to daily data shows good results, especially because we calibrated the stochastic model on the available daily observation series. The accuracy of the daily precipitation, however, depends on the veracity of the monthly precipitation simulations (*P*) of the SIMPA model.

Furthermore, hydraulic properties of the soil should be taken into account. The lack of high-resolution edaphologic information significantly affects the precision of the results. Differences of green/blue water consumption ratio of up to 7% are found, depending on the criterion used. Running the models with a range of TAWC values can improve the results of the models. However, this also increases computer time.

The calculation of the WF by spatial water balance models, rather than by models with a national or regional resolution, provides more reliable outcomes: The spatial inhomogeneity of the data, such as climatic or soil variables, is considered. Administrative boundaries moreover rarely coincide with hydrographical boundaries. Hence, such models improve the basin-level analysis and allow to analyse the results in the spatial context.

The results obtained with the CWUModel resemble the results obtained by Mekonnen and Hoekstra for the same study area, with variations in both the WF of the crop, and the WF of the entire basin. However, the accuracy of this study is increased by improving the resolution of the water balance cells and the input data entered.

Finally, this tool could be used by the hydrographical confederation to comply with the mandate of the Spanish Ministry of Agriculture, Food and Environment, which stipulates the obligation to include a water footprint analysis in the "River Basin Plans" established by the Water Framework Directive (Garrido et al., 2010).

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4. The water footprint of Austria: Why a healthy diet will be more sustainable

D. Vanham

Institute for Environment and Sustainability, Joint Research Centre, European Commission, Ispra, Italy

Abstract

Within this paper, the water footprint of consumption (WF_{cons}) of Austria for different diets is analysed: the current diet (period 1996-2005, REF), a healthy diet (DGE) and a vegetarian (VEG) diet. The consumption of agricultural products is responsible for a very large fraction of the WF_{cons}. Especially the consumption of livestock products (meat, dairy products and eggs) generally increases the WF_{cons} substantially. The current total Austrian WF_{cons} amounts to 4377 l/cap/d, of which 83% relates to the consumption of agricultural products. However, both the daily consumption and intake of kcal and the proportion of animal proteins are considerably higher than recommended. It is shown that both the DGE and VEG diets reduce the WF_{cons} considerably, i.e. by a reduction amount of 879 l/cap/d (20% of the total WF_{cons}) respectively 1318 l/cap/d (30% of the total WF_{cons}). The VEG diet is characterised by the lowest WF_{cons}.

Introduction

The water footprint of consumption (WF_{cons}) of a nation is defined as the total volume of freshwater that is used to produce the goods and services consumed by its inhabitants. The consumption of agricultural products contributes by far the largest fraction of the WF_{cons} (Hoekstra and Mekonnen, 2012; Hoekstra et al., 2011). A substantial proportion of the WF_{cons} in western countries relates to the consumption of livestock products (Hoekstra and Mekonnen, 2012; Mekonnen and Hoekstra, 2012). With a total annual per capita meat consumption of 110 kg, Austria was in 2005 fourth in the ranking of countries with the highest per capita meat consumption (FAOSTAT, 2011). A healthy diet is by some authors (Rockström et al., 2007; Rost et al., 2009) – based upon (FAO, 2003) - defined as a daily consumption of 3000 kcal per person with a 20% animal protein share. The per capita daily consumption in Austria was 3725 kcal for the period 1996-2005 (FAOSTAT, 2011). From the average daily protein consumption of 109 grams, 37% came from crop products and 63% from livestock products. Both the daily consumption of kcal and the proportion of animal proteins are considerably higher than recommended. The latter values are consumption values as given by the Food Balance Sheets (FBS) of FAOSTAT (FAOSTAT, 2011). They are not the same as actual intake values, which account for food waste. Actual recommended energy and protein intake amounts are lower (Elmadfa and Freisling, 2009; Walter et al., 2007; WHO, 2003). The World Health Organisation (WHO, 2007) e.g. recommends 2200 kcal/d for a healthy diet. The recommended values are 2500 kcal for young men and 2000 kcal for women, and less for children and elderly people.

In this paper the WF_{cons} of Austria for the current situation (reference period 1996-2005), a recommended healthy diet and a vegetarian diet are analysed.

Data and methodology

Data on food supply quantity (tonnes and kg/cap/yr) of different products are obtained from the Food Balance Sheets (FBS) of FAOSTAT (FAOSTAT, 2011) and intake amounts derived by means of Statistics Austria (Statistics Austria, 2011) data and specifications discussed in Westhoek et al. (2011) and Zessner et al. (2011). FBS food supply data are data on food reaching the consumer. They are on an "as purchased" basis, i.e. as the food leaves the retail shop or otherwise enters the household. To convert food supply to intake data, two correction factors are used as discussed in Zessner et al. (2011). The first factor accounts for food components not eaten and product equivalent conversions (e.g. bones in meat – meat supply in the FBS is given in carcass weight - or wheat equivalent to flour of wheat/bread) and the second for food waste.

The water footprint (WF) accounts of different products are obtained from Mekonnen and Hoekstra (2011) and Vanham (2012a). They include green, blue and grey water. Blue water refers to liquid water in rivers, lakes, wetlands and aquifers. The blue WF refers to the volume of surface and groundwater consumed (evaporated after withdrawal or incorporated in the product) to produce a product. Green water is the soil water held in the unsaturated zone, formed by precipitation and available to plants. The green WF is thus the rainwater consumed by crops. Consistent with these definitions, irrigated agriculture receives blue water (from irrigation) as well as green water (from precipitation), while rainfed agriculture only receives green water. The grey WF is the volume of water needed to dilute a certain amount of pollution such that it meets ambient water quality standards or is equivalent to natural background concentrations (Hoekstra et al., 2011). The WF of agricultural products is in Mekonnen and Hoekstra (2011) calculated by means of the bottom-up approach (Hoekstra et al., 2011), which enables to assess the WF in a detailed way per commodity or product category. The reference period is 1996-2005, because the WF analyses of Mekonnen and Hoekstra (2011) were done for this period.

A healthy diet is based upon the dietary recommendations issued by the *Deutsche Gesellschaft für Ernährung* – DGE (German nutrition society)(DGE, 2012). The latter is used within the German-speaking countries, e.g. resulting in the Swiss food pyramid (Walter et al., 2007). Actual intake values as recommended (the DGE scenario) are compiled based upon a combination of sources, i.e. DGE (2012), Walter et al. (2007) and Zessner et al. (2011). A more detailed description is given in (Vanham, 2012b). Also a vegetarian diet (VEG) is assessed. This diet is based upon the DGE diet, but the meat intake is substituted by an increased intake of products from the group "pulses, nuts and oilcrops". This intake amount is chosen in such a way that the total energy and protein intake of the DGE and VEG diets are identical. Vegetarian diets do not contain meat, poultry or fish; vegan diets further exclude dairy products and eggs (Key et al., 2006).

The WF of consumption of Austria

The total WF of consumption

The total WF of Austrian consumption (WF_{cons}) amounts to 4377 l/cap/d, of which 3% relates to domestic water use, 14% to the consumption of industrial products and 83% (3655 l/cap/d) to the consumption of agricultural products (Figure 1). Of the latter more than half is attributed to the consumption of livestock products.

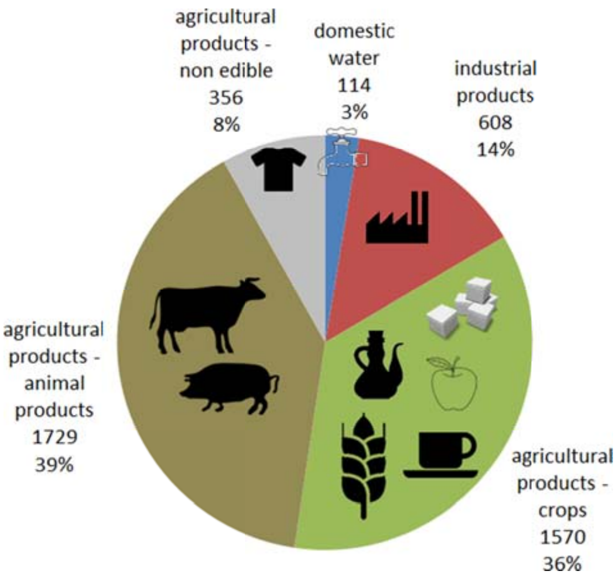

Figure 1. The Austrian WF_{cons} in l/cap/d. The total value amounts to 4377 l/cap/d. Data source: Mekonnen and Hoekstra (2011).

WF_{cons} of agricultural goods – the current (REF), ahealthy (DGE) and vegetarian (VEG) Austrian diet

As recommended by the DGE (Figure 2), the average Austrian diet requires an increase in the consumption of the product groups 1) cereals, rice and potatoes, 2) vegetables and 3) fruit. On the other hand a reduction in the consumption of the product groups 1) sugar, 2) crop oils, 3) meat, 4) animal fats, 5) milk and milk products and 6) eggs is recommended. The values presented in the figure are intake values. The product group pulses, nuts and oilcrops is not specifically covered by the DGE. However, as this group provides for a relatively high proportion of energy and protein intake, it is included in Figure 2. For the VEG diet an additional intake amount of 19.5 kg/cap/yr results in the same total energy and protein intake as the DGE diet. Non-essential edible products like stimulants (e.g. coffee, cocoa and tea) or alcoholic beverages are not included in the DGE recommended diet.

As shown in Figure 3, a shift to the DGE recommended diet would result in a – for the product groups covered by the DGE - WF_{cons} of 1881 l/cap/d instead of the current 2760 l/cap/d (a reduction of 879 l/cap/d or 32%). A shift to the VEG diet would result in a WF_{cons} of 1442 l/cap/d instead of the current 2760 l/cap/d (a reduction of 1318 l/cap/d or 48%). Especially the reduced consumption of meat has a very large impact on the WF_{cons} reduction. The total WF_{cons} for agricultural products (3655 l/cap/d, REF) is reduced to 2776 l/cap/d (DGE) and 2337 l/cap/d (VEG). The total WF_{cons} (4377 l/cap/d, REF) is reduced to 3498 l/cap/d (DGE) and 3059 l/cap/d (VEG).

Additionally a reduction in the consumption of stimulants (especially coffee and cocoa) as well as beer and wine can result in a substantial reduction in the WF_{cons}. These products account for a WF_{cons} of 539 l/cap/d (Figure 3)(coffee 277 l/cap/d, cocoa 129 l/cap/d, wine 72 l/cap/d, beer 37 l/cap/d). With a consumption of 7 kg/cap/yr, the average Austrian coffee consumption exceeds the EU average (4.8 kg/cap/yr). An alternative option can be to import products like coffee preferably from countries where the WF_{prod} is lower and more sustainable (Vanham, 2012a). A reduced intake of alcoholic beverages can also have an impact (Vanham, 2012b). Also for non-edible agricultural products (included in Figure 1, e.g. cotton) a WF_{cons} reduction is possible.

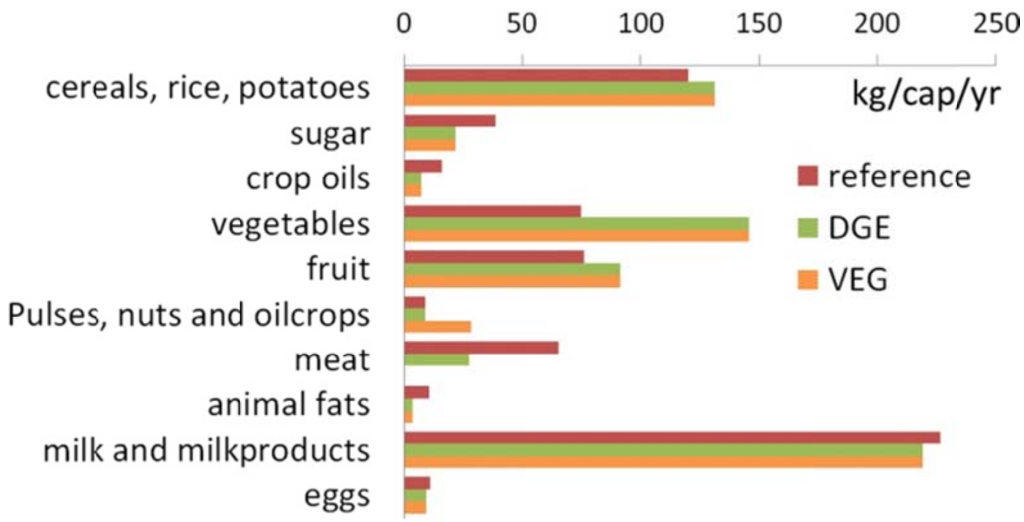

Figure 2. Intake of product groups for the reference period, as recommended by the DGE and the vegetarian diet (VEG). Milk and milk products are expressed as milk equivalent (e.g. 8 litres milk equivalent for 1 kg of cheese). Pulses, nuts and oilcrops are not specifically recommended by the DGE, but are nevertheless included.

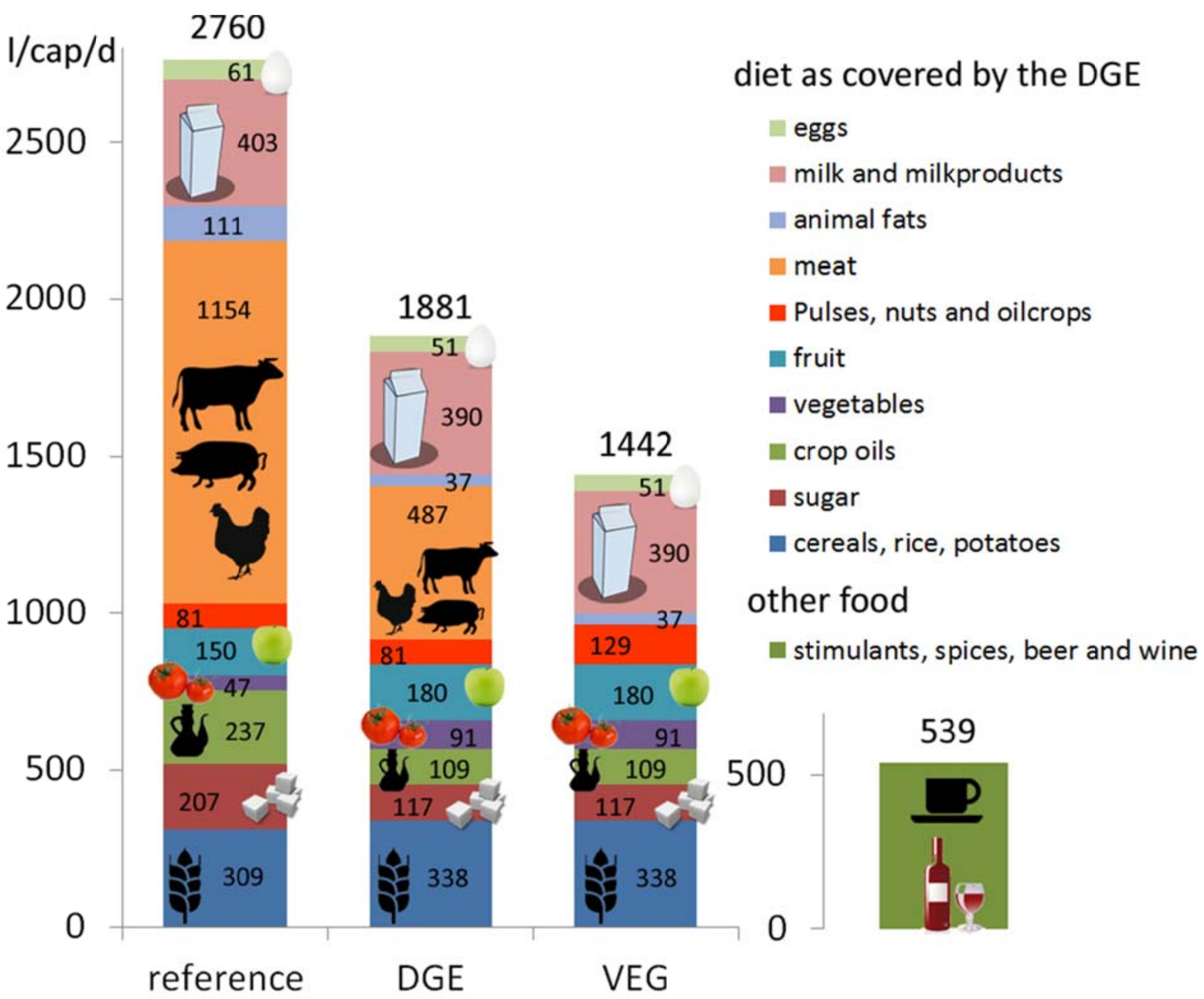

Figure 3. WF of the different product groups covered by the DGE for the reference period, as recommended by the DGE and the VEG diet

Conclusions

The dominant fraction (83%) of the total Austrian water footprint of consumption (WF_{cons} = 4377 l/cap/d) relates to the consumption of agricultural products. The current diet of Austrians is composed of too much meat, eggs, animal fats, milk and milk products, crop oils and sugar. On the other hand the DGE (*Deutsche Gesellschaft für Ernährung* – German nutrition society) recommends an increased consumption of cereals, rice and potatoes, vegetables and fruit. A conversion from the current diet to a healthy diet would result in a WF_{cons} reduction of 879 l/cap/d. A conversion from the current diet to a vegetarian diet would result in a WF_{cons} reduction of 1318 l/cap/d. Additionally, there is a substantial potential to reduce the WF_{cons} within the product group stimulants and beer and wine. Many other western countries have similar diets and a WF_{cons} analysis of different diets should be made.

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5. Applying the water footprint methodology in a cosmetic company: lessons from Natura Cosméticos, Brazil

I.C.M. Francke[1], J.F.W. Castro[2]

[1] Natura Cosméticos, Brazil

[2] Geoklock Consultoria e Engenharia Ambiental, Brazil

Abstract

Even though water is a renewable resource, accessible quality freshwater is becoming increasingly scarce and water-supply security is currently a worldwide concern. The fact that many production processes use freshwater, whether or not incorporated in the product itself, forces companies to turn attention to this issue. Natura Cosméticos, a leading cosmetics company in Latin America, has been strongly committed towards sustainability to create value in its entire supply chain, with a balance between economic, social, and environmental impacts. This paper presents the application of the water footprint concept for the company, based on the whole product life cycle, including the use and disposal phase. It aims to understand the impacts and the applicability of the water footprint concept in order to support sustainability decisions. This study quantifies the direct and indirect fresh water consumption. The results indicate that the direct water footprint of the company can be considered not significant, but the water footprint of energy consumption is more relevant. At the indirect freshwater consumption, the green water footprint is the most representative component in the supply chain due to the agriculturally derived ingredients. The electricity consumed in water supply systems and the inter-basins water transfers are responsible for the large blue water footprint at the use phase. The grey water footprint is the largest component of the study and it is related to the disposal phase of the cosmetics products and mainly determined by the geographical location.

Introduction

Water resources in Brazil

Brazil has always been considered a country rich in water. It is estimated that about 12% of the world's surface freshwater resources are located in the country. However, there is an uneven spatial distribution of water resources in the Brazilian territory. About 80% of all its water resources are concentrated in the Brazilian Amazon Basin region, which is less inhabited and has the lowest values of water demand (Agência Nacional de Águas [ANA], 2011). Additionally, collection rates and treatment of urban sewage are not yet satisfactory. For instance, for the base year 2008, while 50.6% of urban sewage was collected only 34.6 % was treated before being discharged into water bodies (ANA, 2011).

Natura and sustainability

Natura Cosméticos, a leading cosmetic company in Latin America, has been strongly committed towards sustainability to create value in its entire supply chain, with a balance between economic, social, and environmental impacts, for more than four decades. In line with this mission, the company has launched initiatives to minimize its environmental impacts, such as the use of refill packaging, which has been done since the early 1980s. Moreover, starting in 2001 several environmental indicators and associated management systems have been implemented.

The first model of environmental indicators adopted by Natura was a simplified Life Cycle Assessment for packaging, established in 2001. The calculation of aggregate value, in "millipoints" per kilo of content, characterized the relative environmental impact of packaging for each product, and helped initiate Ecodesign practices in the development process. Also, this indicator allowed the calculation of an average value for all packaging of Natura's products that considers the total mass of products sold each month.

In 2007, a second model was adopted by Natura. It was the Environmental Table, a self-declaration label posted on all products and on website. It is composed of 6 indicators of the product content (characterizing the origin of raw materials) and packaging (% of recycled material, % of recyclable material, and number of recommended refills). This model not only aimed at raising consumer consciousness about product-related environmental issues, but has also increased the number of environmental indicators available for sustainability management purposes.

The third model, the Greenhouse Gas (GHG) Emissions Corporate Inventory, was also created in 2007, being the basis for the Carbon Neutral Program. Natura's externally verified Scope 3 Inventory accounts for GHG emissions starting from the extraction of raw materials up to the disposal of final products and packaging. This model was recently updated to include two additional levels of accounting to produce an even more effective support to the Carbon Reduction Program: an inventory split by internal macro-process, and a carbon footprint of all products sold. This reduction effort refers to a publicly reported reduction target of 33% in carbon intensity adopted in 2007 for a seven-year period. The results are followed up quarterly.

Natura and water stewardship

Based on an initial successful experience in Life Cycle Management, Natura has perceived the need to extend the scope of the currently adopted environmental assessment and indicator tools, giving priority to measuring the associated impacts on freshwater. Indeed, within the last five years, society and businesses have shown increasing concern about water as a key challenge to long-term sustainability. The World Business Council for Sustainable Development (WBCSD), a global association of companies dealing with business and sustainable development, believes that businesses can play an active and responsible role in ensuring socially equitable, ecologically respectful, and economically viable water management.

With that in mind, Natura began a series of studies to support the future implementation of a freshwater sustainability strategy, considering the three main pillars involved in the current Carbon Program: quantifying, reducing, and offsetting the impacts.

The Water Footprint concept

For quantifying the associated impacts on freshwater, we chose to apply the water footprint (WF) concept. Firstly introduced by Hoekstra (2003), WF is an indicator of freshwater use that considers both direct and indirect water use of a consumer or producer. Water use is measured in terms of water volumes consumed and the water that is polluted per unit of time. Consumption refers to the volume of freshwater lost by evaporation or incorporated into a product. From the water resource point of view, consumption is the freshwater withdrawn that does not return directly to its original source.

It is important to consider the different components of WF separately. The green water footprint refers to the total rainwater evapotranspiration from fields plus the water incorporated into harvested products. The blue water footprint is an indicator of consumptive use and is defined as the volume of surface and groundwater consumed as a result of the production of a product or service. The grey water footprint is an indicator of freshwater pollution that can be associated with a product's life cycle. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011).

The distinction between the green and blue water footprint is important because the hydrological, environmental, and social impacts, as well as the economic opportunity costs of surface and groundwater use for production, differ from the impacts and costs of rainwater use. Furthermore, evaluation of green and blue water in agricultural systems indicates irrigation practices and local surface water demands.

To better understand the impacts and the applicability of the water footprint concept, we carried out a pilot project in partnership with the Water Footprint Network (WFN, www.waterfootprint.org). Two cosmetics from the product portfolio were chosen, a perfume and a body oil, and the water footprint concept was explored and quantified considering the life cycle approach and applying the methodology described by Hoekstra, Chapagain, Aldaya, & Mekonnen (2009). The scope and boundaries were defined as widely and inclusively as possible, considering the green, blue, and grey water involved through the complete life cycle of the products: extraction of raw materials, production processes, and consumer use phase. We concluded that it is possible to apply the water footprint methodology to build a consistent freshwater corporate inventory and to be used for product analysis.

As the next step, we started a water footprint inventory of Natura to understand the potential impacts on freshwater associated with our activities. This report will describe our initial efforts in measuring the total water footprint of the business of Natura, considering the life cycle of all its products produced in 2010.

Methodology

To assess the volumes of water required, we used the water footprint definitions and methodology as described by Hoekstra *et al*. (2011).

Business water footprint

The accounting of water use by economic activities, also termed "corporate or business water footprint," refers to the total volume of water consumed directly and indirectly for the supply of economic activity (Gerbens-Lennes & Hoekstra, 2008). The water footprint of a business consists of two components: the direct water footprint, which refers to the freshwater consumption and pollution associated with the production of product units, and the indirect water footprint, related to the water consumption in the producer's supply-chain and also by the consumers, when using the product.

Considering the reality of a cosmetics industry and the characteristics of Natura's environmental approach of its business model, the following stages were defined based on our product's life cycle (Figure 1):

- Supply chain water footprint: water consumption associated with all inputs in the supply chain (product ingredients and packaging materials).
- Operational water footprint: water consumption associated with the production of product units and to support operating activities of the business.
- Distribution water footprint: water consumption associated with the logistics of the distribution of products: home delivery of products to consultants (sales representatives).
- Use phase water footprint: water consumption associated with the use of products by consumers.
- Disposal phase water footprint: water consumption associated with potential changes in quality of water resources as a result of the disposal of a product after its use by the consumer.

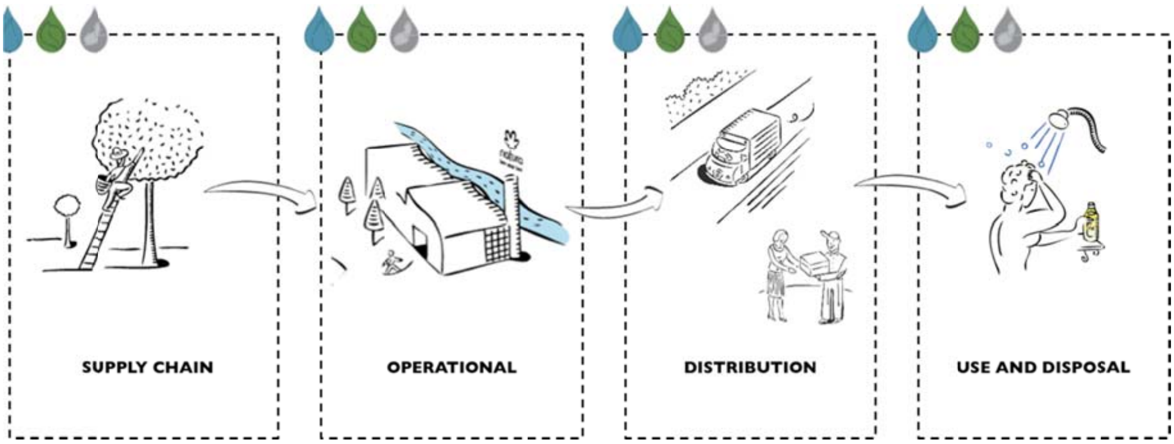

Figure 1. Life cycle of Natura's products.

Water footprint of electricity

The values of water footprint for electricity production in Brazil were obtained through a combination of data from the average generation of main Brazilian electricity sources (Agência Nacional de Energia Elétrica [ANEEL], 2011) and the water footprint data described by Gerbens-Leenes and Hoekstra (2008), and Mekonnen and Hoekstra (2011). In addition, information from Brazilian hydroelectric plants was incorporated in the calculation framework when available (Mekonnen & Hoekstra, 2011; Mekonnen & Hoekstra, 2012). Hydropower electricity represents 70% of the total Brazilian electricity source generation.

For global data we followed the same approach using a global energy matrix comprised of 16% hydroelectricity and 84% fossil fuels (Mekonnen & Hoekstra, 2011).

Water footprint of fuels

The water footprint values for fossil fuels, including bio fuels, were obtained from the combination of water footprint values described by Gerbens-Leenes, Hoekstra, and Van Der Meer (2008), Mekonnen and Hoekstra (2011), and information on heating value gathered from the Brazilian National Energy Balance (Empresa de Pesquisa Energética [EPE], 2011). The primary energy average WF (excluding biomass) adopted from Gerbens-Leenes, Hoekstra, and Van Der Meer (2008) were equally allocated as blue and grey WF.

Supply chain

The supply-chain water footprint relates to all product inputs, and consists of the following components:

- Water footprint of product ingredients other than water.
- Water footprint of packaging materials.
- Water footprint of supporting material for consultants (sale representatives) – magazines, cardboard boxes, and paper bags.

For all inputs, we considered the water consumed (green and blue WF) and potentially polluted (grey WF) in all life cycle stages, from extraction to manufacturing, as well as the WF of electricity and fuel consumption.

Database screening

A preliminary study contemplating the consumption of water for all product inputs was completed through database screening (Ecoinvent 2.1). The main focus of the study was to understand the potential blue water footprint of different materials in relation to the amount in kilograms consumed.

A ranking list called the "ABC List" that included all materials was created to indicate the most representative inputs in terms of blue water footprint, thus defining the items to be mapped with greater or lesser detail, according to their contribution to the total water footprint:

- List A - materials with major contribution: processes were mapped directly with Natura’s suppliers and primary data were collected (80% of the blue water projection);

- List B - materials with average contribution: mapped through databases and data modelling from literature (80–90% of the blue water projection);
- List C - materials with low contribution: water footprint determined by similarity with other materials from Lists A and B (remaining materials).

To address all different types of input with reliable data that would reflect Natura's business reality, a list of categories was created considering specific characteristics. Each category had a representative material included in List A. For instance, the hydrocarbon category represents a small part of the total contribution and should be excluded from the list based on the adopted criteria. However, evaluation of at least one material of this category was important in order to understand its impacts and also to generate a database that would consider all categories.

The use and disposal stages were not considered in the screening and prioritization process, since the concept of water footprint at these stages is specific as to how the product is used and to which water body it is discharged. It is not an intrinsic characteristic of the material.

Water footprint data for product inputs

For all materials addressed in List A, a survey was conducted with the suppliers, gathering data for water consumption, wastewater generation, energy consumption, and production for 2010. We adopted an input cut-off of 1%; i.e., materials or fuel chain representing less than 1% of the total mass were ignored.

The information on the water footprint of remaining materials was searched in the WFN publications, and when not available was calculated based on data from the supporting database. For this study an improved database version of Ecoinvent, the Quantis Water DataBase (www.quantis-intl.com), was consulted in its developing phase. The database project was an initiative led by Quantis and a consortium of companies, including Natura. Also, water taken from surface sources, the electricity consumed in the processes, and the polluting elements of greater impact were used in calculations. The quality parameters for effluent discharge used were from the Brazilian National Legislation (CONAMA, 2005).

As for the agricultural stages, we considered that 10% of the nitrogen applied reaches the water body, as suggested by Mekonnen and Hoekstra (2011). Given this parameter, the maximum concentration of release allowed was considered as 20 mg/l of nitrogen (CONAMA, 2011).

Natura's operations

At this stage, the boundary was set by the operational activities of Natura's sites. To have a better understanding of the main impacts associated with the operations, the WF was divided into two categories: direct and indirect operational WF.

Direct operational water footprint

The direct operational WF was considered as water consumption based on the water mass balance of business product units, using data of water abstraction, water consumption, and wastewater discharge volumes. Water consumed in kitchens, toilets and gardening activities – overhead water footprint – was also included.

For the grey water footprint calculation, concepts of maximum admissible concentration and natural concentration of the water resource were used. The difference between the river natural concentration (C_{nat}) and the maximum concentration that the river can assimilate (C_{max}) indicates the pollutant load amount that the river can receive. Thus, the pollutant load (L) launched through effluents, divided by the assimilation capacity (C_{max} – C_{nat}), represents the water volume that the water resource has to provide for the natural assimilation of this quality change, due to the pollutant load launched in the water body.

Green water footprint was not calculated because the company does not operate any agriculture plantation system for economic purposes.

Indirect operational water footprint

The indirect operational WF refers to the water footprint associated with the use of electricity, fuels, and bio fuels by Natura's operations. Since it does not represent a direct consumption of water but is still essential to support operating activities, it was defined as indirect operational WF. The calculations were based on the electricity and fuels WF previously described in item 2.1 and 2.2, and the consumption based on data from 2010.

Distribution logistics for product delivery

Natura has adopted a direct sales business model, with more than 1.4 million consultants (sale representatives) to disseminate the value proposition to its consumers (Natura Annual Report, 2011). The water footprint related to the stage of distribution results from the water consumption associated with the electricity and fuel required to transport and deliver Natura's products to our consultants. The calculations are based on the energy WF previously defined in item 2.1 and 2.2 and electricity and fuels consumption data for Natura in 2010.

Use and disposal of products

Consumptive use

We assumed that the consumptive use corresponds to the urban water cycle between capture and return to the water body, covering the losses of the system of water supply, distribution, sewage collection, and treatment. In order to quantify the blue water from the use of products, the loss rates in the system of water supply were surveyed. These data were obtained from the Brazilian national information system on sanitation (Ministério das Cidades, 2009).

Inter-basin water transfers were also considered in the analysis. To supply regions with water scarcity and serve local populations, the transfer of water between different basins is required. An inter-basin water transfer is the abstraction of water from a river basin and transferring it to another river basin. According to the blue water footprint definition, taking water away from a river basin contributes to the blue water footprint within that basin, because it is 'consumptive water use' (Hoekstra et al., 2011). This water never returns to its origin river basin. The main cases of inter-basin water transfers in Brazil occur in the metropolitan areas of Rio de Janeiro, São Paulo, Salvador, and Fortaleza (ANA, 2010).

Electricity is also essential for the production and availability of clean water to the consumer. Thus, in order to calculate the water footprint of the use phase, the average energy consumption from water treatment plants was considered. The water footprint of electricity was calculated through the electricity and fuels WF described in item 2.1 and 2.2.

Water use demand

For each category of products (for example: soaps, shampoos, moisturizers, etc.), we analysed the water needed by the consumer to use Natura's products. For categories associated with water usage, a water use volume was assumed, according to the related personal care activity. Recommended water volumes for bathing, hand cleaning, and shaving were obtained from the local sanitation authority (Companhia de Saneamento Básico do Estado de São Paulo [SABESP], 2011). For bathing, the total water use volume was allocated for each of Natura's bathing sub-categories (shampoo, hair conditioner, body oils). This allocation was prepared based on a small survey among Natura's Research & Development team.

The energy associated with bathing (heating water) and other personal care activities was not considered in this study due to the high-amplitude climate in Brazil. Furthermore, we assumed that the energy use is more related to the consumer profile than to product demand.

Disposal of products

We analysed the environmental laws and water use characteristics of each state in Brazil, searching for a better understanding of the local situation of water resources and sanitation scenarios. This allowed us to define *regional factors* for the use and disposal stages, and obtain more representative water footprint results considering local aspects.

Once the product is disposed, it will contribute to the wastewater share of the household. Three different possible scenarios were identified:

- Wastewater is collected, treated, and released into water bodies.
- Wastewater is collected and released into water bodies, without treatment.
- Wastewater is discharged directly into local water bodies.

These scenarios were described in order to process the data and calculate *regional disposal factors*, taking into account the fact that wastewater collection and treatment is directly linked to the pollutant load released into water bodies.

Among Natura's ingredients evaluated, those with greater relevance in mass contained a large percentage of carbon molecular chains in their composition. Therefore, the BOD_5 (biochemical oxygen demand) was an appropriate parameter to quantify their impact on water resources. In addition, legislation for effluent discharge, and consequently the assessment of compliance with discharge standards, is usually based on BOD_5 (Von Sperling, 2005). Therefore, we chose the parameter BOD_5 for the evaluation of grey water footprint of products.

To calculate the potential pollutant load released into local water bodies, the data on the volume of sold products by category and the rate of wastewater treatment in Brazil were considered for each city (Ministério das Cidades, 2009).

It was assumed that all treatment systems have an efficiency rate equal to 80%, the minimum value set by CONAMA (2005) for wastewater treatment.

Electricity is essential for the wastewater treatment process as well. Once the product is disposed by the consumer and becomes effluent, it may be treated before reaching the water bodies. The average energy consumption from wastewater treatment plants (Ministério das Cidades, 2009) was also considered in the disposal phase data. The water footprint of electricity was calculated through the electricity and fuels WF described in item 2.1 and 2.2.

Data analysis

To calculate the use and disposal water footprints of Natura, a mathematical model was adopted to evaluate the amount of water consumed as well as the pollution generated as wastewater by consumers while using Natura's products. Water use and pollution disposal values were defined for each category considering the characteristics of each personal care activity.

The volume of sales in 2010 was analysed based on the specific environmental characteristics and legislation of each region and/or state in the country where the product was sold. *Regional WF factors* for use and disposal were defined for each of the 27 Brazilian states, considering the circumstances of local sanitation and water resource management. For the WF regional factors of the use stage (representing local aspects of water use), basin transfers and water lost in the supply system were considered. As for WF regional factors of disposal stage (representing the potential pollutant load that reaches the water bodies), the rate of wastewater treated was the main data used. All calculations were based on the following equations:

$$WF_{use,\ k} = \sum_{i,j} M_{i,j} \times WU_i \times UWF_{j,k} \tag{1}$$

where:

WF_{use}	= Water footprint of the use phase	[l]
M	= mass of products sold	[kg]
WU	= water use allocated by category (water use demand)	[l / kg]
UWF	= regional WF factor for water use (local aspects of water supply and resources)	[l / l]
i	= product category (i=1 to 13)	
j	= region zone i (i=1 to 27) Brazilian states	
k	= water footprint component: green, blue and grey (k=1 to 3)	

$$WF_{disposal,\ k} = \sum_{i,j} M_{i,j} \times PL_i \times PWF_{j,k} \tag{2}$$

Where:

$WF_{disposal}$	= Water footprint of the disposal phase	[l]
M	= mass of products sold	[kg]
PL	= pollution load allocated by category (load disposed after use)	[mgO_2 / kg]
PWF	= regional WF factor of load disposal (local aspects of sanitation)	[l / mgO_2]
i	= product category (i=1 to 13)	
j	= region zone i (i=1 to 27) Brazilian states	
k	= water footprint component: green, blue and grey (k=1 to 3)	

Results

Water footprint of electricity

In order to accurately determine Natura's water footprint, it was first established the Brazilian and global energy WF values that could then be applied to all calculations for energy water footprint.

Table 1. Water footprint values for electricity.

	Green WF (L/kWh)	Blue WF (L/kWh)	Grey WF (L/kWh)
Electricity (Brazil)	7.8	104.6	0.4
Electricity (Global)	-	39.7	-

Table 1 reveals that blue WF is the dominant value for both the Brazilian and global electricity. Furthermore, the Brazilian blue WF is 2.6 times larger than the global average. Green and grey WF are related to thermal sugarcane biomass electrical power plants.

The green water footprint in the Brazilian electricity is related to the biomass sources. The grey water footprint may be underestimated as in the reference data (Gerbens-Leenes & Hoekstra, 2008). This value is based on electricity generation and not on consumption. Thus, as electricity consumption is lower than generation, due to distribution grid losses, the electricity water footprint may in fact be higher.

Water Footprint of Fuels

Fuels are consumed during all life cycle stages of a product. Table 2 shows the efforts on gathering the water footprint averages for the main fuels used by Natura's business.

Table 2. Water footprint of fossil fuels.

Fossil Fuel	Unit	Green WF (L/unit)	Blue WF (L/unit)	Grey WF (L/unit)
Fuel oil	L	-	18.8	18.8
Liquefied petroleum gas	kg	-	2.5	2.5
Diesel oil	L	-	18.8	18.8
Biodiesel (soy)	L	10,825.0	374.0	198.0
Diesel + 5% biodiesel	L	541.3	36.6	27.8
Gasoline	L	-	17.6	17.6
Ethanol	L	1,400.0	575.0	132.0
Gasoline + 24% ethanol	L	332.5	150.0	44.8
Natural gas	m3	-	2.0	2.0

The data indicate that agriculture-derived energy sources, biodiesel and ethanol, contribute to the highest water footprints. Indeed, biodiesel data were the highest in green WF and grey WF. In contrast, two of the fossil-derived sources, natural gas and liquefied petroleum gas, produced the smallest values for all three indicators.

The water footprint of fossil fuels was based on WFN data (Gerbens-Leenes, Hoekstra, & Van Der Meer, 2008). In that study the values represent the full water footprint and were not separated into green, blue, and grey water footprints. Those values were adopted but divided equally between blue and grey WF, for the fossil fuels. The bio fuels values were calculated from agricultural products, as green, blue, and grey water footprints.

Supply chain water footprint

The total water footprint of Natura's supply chain was approximately 268 million m^3, as shown in Table 3.

The water footprint of Natura's supply chain represented 36.7% of the total. The data indicate that the green WF, in reference to the derived agricultural products, has the highest contribution in Natura's supply chain water footprint (76.6%), followed by the grey WF (17.4%), and blue WF (6.0%).

Table 3. Water footprint of Natura's supply chain, year base: 2010.

Material	Green WF (m^3)	Blue WF (m^3)	Grey WF (m^3)
Product ingredients	165,609,638	7,119,895	49,375,109
Packaging materials	33,217,147	9,271,869	3,583,556
SUBTOTAL	198,826,785	16,391,764	52,958,665

Operational water footprint

The direct water footprint of Natura's operations is 0.2 million m³, including contracted manufactures and international sites. Considering the total water footprint of Natura, this stage is negligible (0.03%). Results displayed in Table 4 show that 64% of the total direct operational WF is generated by the sites - factories and offices - located in Brazil, the main territory of Natura's business.

Table 4. Direct water footprint of Natura's operations, year base: 2010.

Unit	Blue WF (m^3)	(%)	Grey WF (m^3)	(%)	Total WF (m^3)	(%)
Natura Brazil sites[1]	78,370	75%	45,562	52%	123,932	64%
Contracted manufacters[2]	9,421	9%	42,086	48%	51,507	27%
International operations[3]	16,706	16%	0	-	16,706	9%
TOTAL	104,496		87,649		196,145	

[1]Natura Brazil sites refer to the units of Cajamar, Alphaville, Benevides, Natura Houses, Distribution Centers (DCs) and Outposts.

[2]Contracted Manufacturers are companies that manufacture finished products on behalf of Natura.

[3]International Operations contemplate Natura's offices located in Argentina, Chile, Colombia, France, Mexico, Peru.

On the other hand, the electricity and fuel consumed directly by Natura's Operations, the indirect WF shown in Table 5, represents 1,3% of the total. Electricity (46,9%) and ethanol (36,2%) represented the major contributions, being the main fuels used in the manufacturing process.

Distribution water footprint

The distribution stage represents 2.1% of the total water footprint of Natura (Table 6). The green WF is the largest indicator within that phase (74.3%), followed by the blue WF (19.3%) and the grey WF (6.4%).

Table 5. Indirect operational water footprint of Natura's operations - electricity and fuels.

Type of Energy	Green WF (L)	Blue WF (L)	Grey WF (L)
Electricity	330.116	4.414.708	18.830
Diesel + 5% biodiesel	742.993	50.175	38.095
Fuel Oil	-	6.017	6.017
Liquefied petroleum gas	-	2.085	2.085
Natural gas	-	19	19
Gasoline+ 24% ethanol	430.343	194.141	57.968
Ethanol	2.448.200	1.005.511	230.830
Jet fuel	-	36.260	36.260
TOTAL	3.951.652	5.708.916	390.104

Table 6. Water Footprint associated with the delivery of products to sales representatives.

Type of Energy	Green WF (L)	Blue WF (L)	Grey WF (L)
Electricity	17,201	230,030	981
Diesel + 5% biodiesel	6,315,597	426,497	323,813
Diesel oil	-	51,490	51,490
Liquefied petroleum gas	-	10	10
Natural gas	-	1,365	1,365
Gasoline+ 24% ethanol	3,025,842	1,365,049	407,586
Ethanol	2,366,526	971,966	223,130
TOTAL	11,725,166	3,046,407	1,008,375

Use and disposal water footprint

The water footprint of the use and disposal stages represents 59.6% of the total water footprint of Natura. In the use phase, the blue WF is the most relevant of the three indicators (98.8%), mainly as a result of water consumed in bath rituals of the consumer (shower, washing hands, etc.). It is important to emphasize that this number is associated with water lost in the system considering the water use cycle (abstraction, use, and discharge).

Table 7. Water footprint of the use and disposal phase, considering consumer rituals.

	Green WF (L)	Blue WF (L)	Grey WF (L)
Use WF (water consumed)	-	89,174,925	-
Use WF (electricity)	1,224,624	16,377,138	69,852
Disposal WF (water consumed)	-	-	348,632,701
Disposal WF (electricity)	87,481	1,169,896	4,990

Furthermore, for the disposal phase, the grey WF was the most relevant of the three indicators (99.6%) in reference to the water potentially polluted through the use of products by consumers and the characteristics of local sanitation.

Total water footprint of Natura's business

Natura's business water footprint, in which the whole life cycle of its portfolio of products, is considered is presented in Figure 2 by stage and type of water.

The grey WF constitutes 52.3% of the whole water footprint evaluated. The highest numbers are found in the disposal phase where it constitutes 99.6% of the total for this stage. The green WF constitutes 30.5% of the whole water footprint, being the most relevant in the supply chain phase where it reaches 76.6%. The blue WF has the smallest impact, contributing 17.2% of the whole water footprint of Natura's business. The use phase presents the highest rates for this indicator (79.4%). The operational phase caused the least impact on all three water footprint indicators (1.3%), with blue WF (56.4%) and green WF (38.9%) being the most representative at this stage.

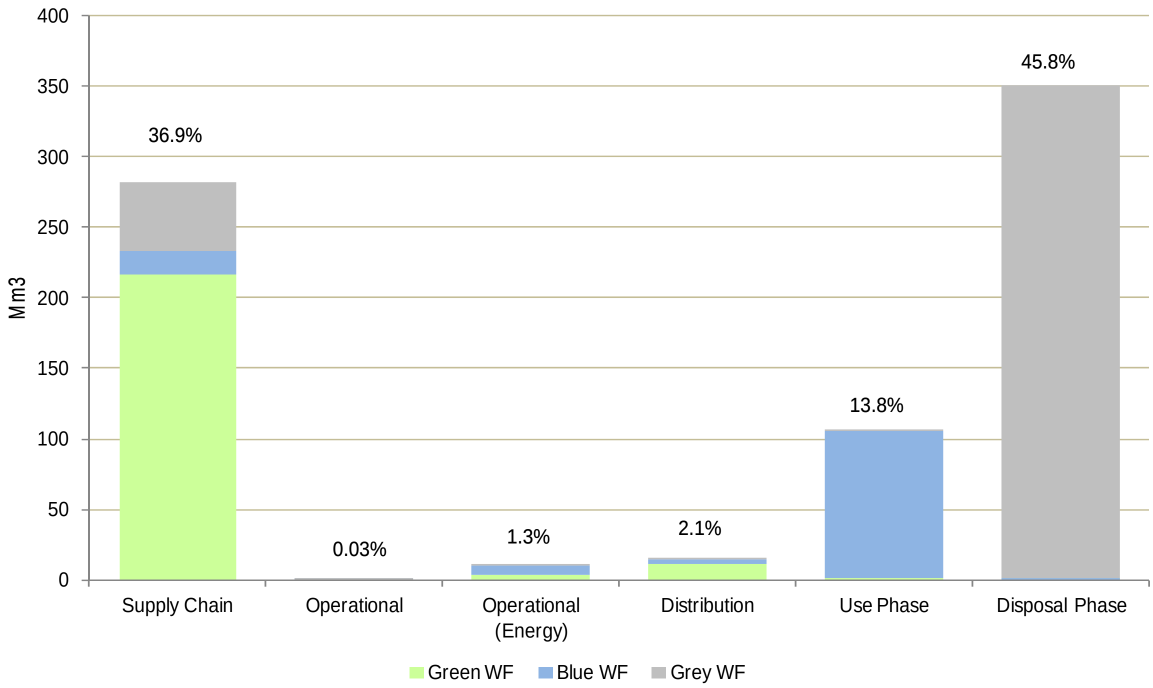

Figure 2. Water footprint of Natura's business, considering all stages of the products' life cycle.

Discussion

The total water footprint of Natura's business was calculated considering the life cycle stages of all its products produced in 2010. The results present the grey WF as the largest indicator (52.3%), followed by the green WF (30.5%) and the blue WF (17.2%).

The operational water footprint associated with energy consumption, electricity and fuels, represents 1.3% of the total water footprint. The blue and green WFs are the largest indicators at this stage. These results may be explained by two factors: the Brazilian energy matrix, composed mainly by hydroelectricity (70%), and the use of bio fuels such as ethanol and biodiesel (ANEEL, 2011). The former generates a large blue WF, as described by Mekonnen et al.(2011), and the latter a large green WF because the main fuels are derived from agricultural products (Mekonnen & Hoekstra, 2011). In any case, the results indicate that the operational WF does not have a significant impact, when analysing the whole life cycle of products. These findings agree with those in a study of the beverage industry, where the operational water footprint of beverages was negligible when compared to the water footprint of the ingredients (Ercin, Aldaya, & Hoekstra, 2011). Natura's operational water footprint of the production process is remarkably small when compared to the total WF.

The supply chain water footprint constitutes 36.9% of the total water footprint of the business in 2010. The green WF is the largest indicator, corresponding to 76.6% of the total of the supply chain stage. These results may be explained by the agriculturally derived ingredients used in the formulations of Natura's products. As one of Natura's corporate strategies, it was decided back in 2000 to incorporate biodiversity assets into products in a sustainable manner, always respecting the ways of traditional communities and the livelihoods of local families (Natura Annual Report, 2011). As a direct result, the green WF is highly representative, but does not necessarily reflect an impact on the environment and local water resources. To insure the sustainability of Natura's supply chain, the river basins where main agricultural activities are located were studied, considering the status of water resources described by the Brazilian national water agency (ANA, 2011). No critical impacts were identified in those areas.

The distribution water footprint by the direct sales business model adopted by Natura has a small contribution to the total WF of the business (2.1%). This contribution is mainly composed of green WF (74%) due to the use of bio fuels. This is a direct result of the Carbon Neutral Program that aims to reduce greenhouse gas (GHG) emissions, since bio fuels have lower GHG emission factors. The green WF is not an indicator of negative environmental impact, and therefore it is not seen as a critical point of action.

The use and disposal phase are the largest contributors to the total WF, resulting in 59.6% of the total WF. This is related to the nature of the products in the personal care and cosmetics industry, which in most cases require water for its use. Shampoos, conditioners, and soaps, among others, demand a significant amount of water that cannot be ignored. This creates a water footprint of not only the use phase, but of the disposal phase as well. Once the product is rinsed, the wastewater generated returns to the environment, and it may be discharged with or without previous treatment. In Brazil, this is not a favourable scenario as only 34.6% of the wastewater is treated before returning to the environment (ANA, 2011). Since Natura's business main focus is in Brazil, the use and disposal phase is extremely relevant to the total water footprint of the company. Even though Natura's role is limited in this respect, some measures can be taken. Techniques of Ecodesign and consumer awareness are among these measures and new efforts are being planned in this direction.

This study depends on several considerations and data assumptions, with associated uncertainties that should be considered when analysing the final results. Even though direct supplier data collection and estimating local factors were the approaches adopted to reduce these uncertainties, only the major suppliers have their data verified in their facilities. Also, some water footprint data used were global numbers and regional values could vary significantly for the same material, depending on the extraction and/or production location.

For the grey WF of the disposal phase, one specific parameter had to be chosen for calculations, as Natura's product portfolio is too diversified. The biochemical oxygen demand (BOD_5) was considered as the most relevant based on product formulations, but other elements could be found to be more relevant if each product was evaluated individually. For a portfolio so diversified and in constant change - in 2011 alone, 164 news products were launched (Natura Annual Report, 2011) - evaluating each product individually would be an impossible task.

Furthermore, the results are impacted by the public water supply and wastewater treatment systems. The water from inter-basin transfer practices, used to meet water demand in some regions, was included in this study. Future water transfers would directly increase the water footprint of supplied water. In the other hand, the wastewater treatment scenario tends to be improved if public investments are made consistently in the future, thus the water footprint at the disposal phase could be significantly reduced.

Conclusion

This study shows that the water footprint of a cosmetic product is very sensitive to the use and disposal locations. Even though the supply chain and operational sites are kept constant, the water footprint of Natura's product significantly changes depending on the category of product and consumer geographical location.

While most companies focus on their own operational performance, this report shows that it is important to address the entire life cycle of products for freshwater usage. In the personal care and cosmetics industry, the use and disposal phase by consumers is as relevant as the supply chain phase, since water is essential to achieve the expected performance of its main products.

This is the first study quantifying the total water footprint of a company, considering the whole life cycle of its products. It brings a better understanding of major impacts on local water resources, and is essential to support sustainability decisions. In the next years, the knowledge and experience acquired will be used to develop a specific freshwater sustainability strategy and actions to drive eco-efficiency. While working in the establishment of guidelines and tools to support this process, Natura has defined water as being one of the priority sustainability topics, and is continuously investing in the reduction of water consumption in its sites with specific commitments and targets defined annually.

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The Netherlands

Website www.unesco-ihe.org
Phone +31 15 2151715

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