The water footprint of a river basin with a special focus on groundwater: The case of Guadalquivir basin (Spain)☆

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ABSTRACT

In addition to revealing the hidden link between products or consumption patterns of populations and their needs in terms of water resources, the water footprint (WF) indicator generates new debates and solutions on water management at basin scale. This paper analyses the green and blue WF of the Guadalquivir basin and its integration with environmental water consumption, with a special emphasis on the WF from groundwater and its consequences on current and future depletion of surface water. In a normal year, green WF (agriculture and pastures) amounts to 190 mm on a total green water consumption of 410 mm, while the blue WF (50 mm) represents half of the total blue water flows. This constitutes a first overview and alternative interpretations of the WF as human water appropriation are introduced. The blue WF is almost entirely associated to agriculture (40 mm). The presentation of its evolution over the period 1997–2008 reveals the rising WF from groundwater (13 mm in 2008), 86% being current consumption of surface flows. This evolution is particularly ascribed to the recent development of irrigated olive groves from groundwater. To prevent a higher pressure on the environment, this new use, like all others (thermo-solar plants, tourism, etc.),

could have been obtained from the reallocation of water from crops with low water productivity. It means that water is not lacking in the Guadalquivir basin if the governance setting integrates more flexibility and equity in the allocation of water to address climatic variability and the emergence of new demands.

1. Introduction

The water footprint (WF) indicator addresses the issue of the appropriation of water resources by humanity [1]. Similarly to the ecological [2] and carbon [3] footprints, the rationale of the WF assessment is initially based on a consumer perspective, since it quantifies both the direct and indirect (i.e. on the whole supply chain) use of water in the elaboration of products or associated to the consumption pattern of a person or a population. A whole range of studies have addressed the WF of a variety of products [4,5] or populations within nations [6,7] or other geographical areas [8]. Meanwhile, it represents an innovative approach on the situation of the world's freshwater resources, for instance introducing the issue of equity in their repartition through virtual water trade or emphasizing the role of consumers and the impacts of their choices [1,9–11]. The corporate sector has also emerged as a new key actor since it constitutes the link between producers and consumers and is also involved through the new paradigm of "corporate social and environmental responsibility" [4,12].

In complement to this first approach, another view from footprint indicators is based on aggregating footprints of the productive processes occurring at the scale of a specific geographical area [1,11,13]. It allows assessing the sustainability relatively to the use of the own internal resources of the region. In relation to water, this perspective can be especially meaningful when the area considered is a river or aquifer basin, since it represents the scale where water resources are physically connected. Various studies have been published following this perspective [11,14–16]. Concerning blue water (i.e. water flowing through rivers and aquifers), the specificity of the WF in terms of water resources appropriation by humanity is to compute only the consumptive use (i.e. water not available again in the river basin for other users) associated with a specific use or process [1]. It contrasts with common indicators that focus on water demand or withdrawals. In addition, traditional water planning considers only blue water, although it has been argued that this conventional approach is incomplete, since green water (rainwater stored in the soil) comprises a critical role in food production and towards the integration of water and land policies [17].

Considering the opportunities offered by the WF as a tool for a renewed view on water management, the present study analyzes the WF of the Guadalquivir basin (south of Spain), focusing on the quantitative components (green and blue). The gray WF, which has been proposed to integrate the effect of contamination of water resources in the WF [1], is not considered here. One of the main innovations is to present the blue WF disaggregated for both surface and ground water for the majority of the economic sectors. Additionally, the WF from groundwater distinguishes a component resulting in current reduction of surface water flows and a component implying a delayed impact on surface resources through the consumption of the aquifers' stock. Another advance is a water balance of the WF for the different economic sectors and main land uses, including green water used by forests and pastures. The WF associated to dams is also quantified.

The paper is structured as follows. After introducing the main features of the study area, Section 2 includes the methodology and data sources. A subsection deals specifically with the dynamics of groundwater mobilization and its role at river basin scale. Section 3 is dedicated to the exposition of the results and Section 4 to the discussion of some methodological issues and interpretations of the results, with a particular attention to the formulation and quantification of the WF in the light of the present study. Finally, the main findings are summarized in Section 5.

2. Methods and data

2.1. Study area

The Guadalquivir basin is located in south of Spain (Fig. 1). It is a semi-arid region (rainfall amounts to 535 mm year^{-1}), in which water repartition among economic sectors and the environment implies a relevant and controversial issue for water resources management. It covers 57,530 km^2, 90% of this area
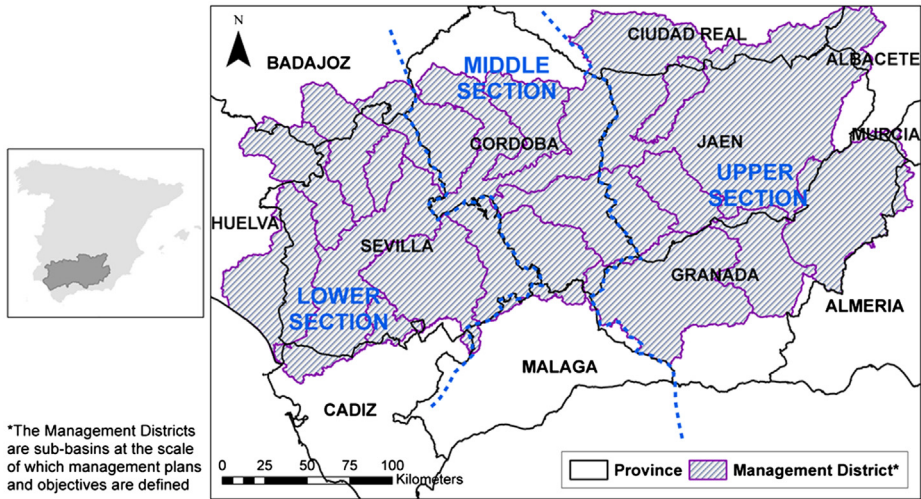
Fig. 1. Localization of the Guadalquivir river and the management districts (adapted from [18]).

being included in the Autonomous Community of Andalusia. The population of approximately 4.1 million is concentrated in the lower stretch of the basin. The Seville Province counts around 2 million inhabitants, being 1.5 million concentrated in the Seville urban area. The secondary and tertiary sectors are also concentrated in this region. Agriculture constitutes an economic activity which extends over much of the territory, with more crop diversification in the lower part of the basin (rice, cotton, olive, cereals, sunflower and fruits). The combination of climatic conditions and topography (mountainous area) in the upper and middle parts of the basin makes these areas particularly suitable for olive groves. In the whole basin of the total cultivated area of about 2.6 million ha, nearly 1.5 million ha was dedicated to olive in 2008. The irrigated olive groves, with 470,000 ha, constitute approximately 60% of the total irrigated area. This situation results particularly from EU Common agricultural policy subsidies that have incentivized the expansion of irrigated olives in the 1990s and also from the major droughts experienced in this period, as irrigating is a kind of insurance towards the reduction of revenues.

The hydrographic network is organized around the 655 km long axis of the Guadalquivir river. The organization in charge of water resource management and planning in the basin is the Guadalquivir river basin authority (GRBA), which depends on the Spanish central government. The assessment of the water bodies status in compliance to the EU Water Framework Directive (EU WFD) resulted in 164 out of 228 surface water bodies and 32 groundwater bodies out of 60 defined in poor status [19].

2.2. Water footprints calculation by sector and origin of water

2.2.1. Water footprint of agriculture

The agricultural WF (in m^3) of the Guadalquivir basin is obtained on an annual basis for the time period 1997–2008 distinguishing green water and the sources of blue water.

$$WF = WF_{green} + WF_{blue\_surf} + WF_{blue\_ground} \tag{1}$$

where WF_{green} refers to the green WF of total agricultural production. WF_{blue_surf} and WF_{blue_ground} comprise the blue WF of irrigated production from surface water and groundwater source, respectively.

WF_{green} is assessed multiplying green crop water consumption (CWC_g in m^3 ha^{-1}) by the area of each crop under rain-fed (S_{rain} in ha) and under irrigated production (S_{irrig}).

$$WF_{green} = \sum((S_{rain} + S_{irrig}) \times CWC_g) \tag{2}$$

CWC_g is calculated as the minimum between effective rainfall (P_{eff}) and crop water requirement (CWR) at a monthly step. CWC_g is summed up over the crop growing period or on the whole year

for perennial trees, following the recommendations of Hoekstra et al. [1]. P_{eff} is calculated based on FAO/AGLW method [20].

$$P_{eff} = 0.6P-10 \text{ for } P \leq 70 \text{ mm}; \; P_{eff} = 0.8P-24 \text{ for } P > 70 \text{ mm} \tag{3}$$

where P comprises the monthly rainfall.

CWR of each crop is estimated following the method of Allen et al. [21], multiplying the reference evapotranspiration (ET_o) by a crop coefficient obtained from literature review [21–23]. Plant and harvesting dates are obtained from MAPA [24].

Monthly rainfall and ET_o are provided by the Spanish meteorological agency [25]. One meteorological station is selected for each of the ten provinces covering the basin. Rain-fed and irrigated crop areas by crop are obtained from regional statistics at municipal level [26].

WF_{blue_surf} is obtained as the sum of the area of irrigated land from surface water source (S_{surf}) multiplied by the blue crop water consumption (CWC_b in m^3 ha^{-1}) for each type of crop.

$$WF_{blue\_surf} = \sum (S_{surf} \times CWC_b) \tag{4}$$

Semi-arid regions, like the Guadalquivir basin, are characterized by high climatic variability and farmers have to cope with irrigation water restrictions. To calculate CWC_b we have to consider a priori that irrigation water requirements are not fully met. In the Guadalquivir basin, 77% of the agricultural demand is satisfied as an average [27] and water delivered to farmers can be restricted by the GRBA during periods of drought. Thus, CWC_b is calculated by multiplying the water allowances (*allow* in m^3 ha^{-1}) for each crop group within each management district (Fig. 1) [22] by the application efficiency (*eff*) to compute only the consumptive fraction of water use. In general, a 85% application efficiency is considered [27] with the exception of paddy fields (50% [28]). Additionally, we reduce irrigation allowances depending on the level of drought in each of the management districts, a measure that is imposed by the Special Plan for Situations of Drought [29]. To do this, we take into account the level of reservoirs' storage by management district [30] and reduce allowances, according to the instructions of the Special Plan, by 5%, 30% or 70% (factor *drought* given as a fraction of unit), depending on the warning drought level of the management district. The final expression of WF_{blue_surf} is given as follows:

$$WF_{blue\_surf} = \sum (S_{surf} \times allow \times eff \times drought) \tag{5}$$

In the case of groundwater, aquifers' stock allows a continuous availability of water, independently of climatic variations. Consequently CWR is considered to be satisfied and CWC_b is obtained as the difference between CWR and CWC_g. The case of olive is specifically considered, as the strategy of deficit irrigation implies that only around half of the CWR is met [31], and a constant CWC_b of 2000 m^3 ha^{-1} is introduced. As the origin of water is not specified in the data set used for crop surfaces [26], detailed groundwater area by crop group was obtained only for the years 1997 and 2002 [32,33]. For the year 2008, data on agricultural groundwater abstractions are available for each groundwater body [19] but without specification of the irrigated crop category. WF_{blue_ground} for 2008 is obtained multiplying the abstracted volumes by an application efficiency (*eff*) of 0,85. Finally, WF_{blue_ground} is obtained from Eq. (6) or (7) depending on data availability for the different years.

$$WF_{blue\_ground} = \sum (S_{ground} \times CWC_b) \quad (years 1997 and 2002) \tag{6}$$

$$WF_{blue\_ground} = eff \times V_{pumped} (year 2008) \tag{7}$$

where S_{ground} (ha) refers to irrigated land from groundwater source for each crop and V_{pumped} (m^3) to the volume of abstractions.

To estimate WF_{blue_ground} on the whole period 1997–2008, a linear evolution between 1997 and 2002 and 2002 and 2008 is considered.

The agricultural WF is also assessed separately for the upper (Ciudad Real, Albacete, Jaen and Granada Provinces), middle (Cordoba and Malaga) and lower (Cadiz, Huelva y Seville) sections of the Guadalquivir basin (Fig. 1). WF_{green}, WF_{blue_surf} and WF_{blue_ground} (1997 and 2002) by crop are summed up for the province. As the data set for WF_{blue_ground} in 2008 does not distinguish the irrigated crop category, it is assumed that the rise in WF_{blue_ground}, as compared to the situation of 2002, corresponds only to olive for the upper and middle sections of the basin [34].

2.2.2. Water footprint of livestock and pastures

The WF of livestock should consider direct and indirect water consumption. The former refers to the water consumption for animal drinking and for farm management. The indirect WF refers to the virtual water embedded into animal feed coming from the internal agrarian production (already accounted in the agricultural WF), pastures and feed imports (WF exerted out of the basin). Thus, the additional WF associated to livestock only includes the direct consumption (obtained from Rodríguez-Casado et al. [35]) and the WF of pastures. The WF of pastures (green water) is estimated considering an evapotranspiration of 1930 m^3 ha^{-1} (J. Corominas, 2011, "Estimación de la huella hídrica y ciclo hidrológico de las cuencas andaluzas", not published) and the pastures area in the basin (6100 km^2 [19]). The whole amount of this WF cannot be assigned to livestock (Section 4.1) and is identified as a separated "pastures WF".

2.2.3. Water footprint of the industry, domestic supply, energy, tourism and dams

The evaluation of the WF for industry, domestic supply, energy, tourism and dams is presented for a unique year (2008). Urban, tourism and industrial WF are estimated from withdrawals data provided by the GRBA [19]. To obtain the water consumptive use for domestic and industrial sectors, return flows of 72% and 44% respectively are considered [19]. Specific data on groundwater abstractions are obtained from the same source for each groundwater body.

The use of water through dams' regulation (particularly for hydropower) is often said to be non-consumptive, as the water is not diverted from the river flow. However, evaporation from the water surface can represent a significant share of the water consumption in the basin [36,37] and should be integrated in the WF balance. It is often disregarded in WF studies even if reservoirs storage is essential to allow many of the uses that are assessed. The volume of water evaporated from reservoirs is calculated according to Hardy and Garrido [38], who established a linear relation between the evaporated volume and reservoir capacity on the basis of a survey of 44 Spanish dams. We consider that all reservoirs are artificial lakes, i.e. the evaporation is human appropriation of water and constitute a WF. The WF associated to dams is not attributed to a specific use as their functions are numerous: electricity generation, storage of water to satisfy demand, flood mitigation, etc.

2.2.4. Water footprint from groundwater: distinguishing current and future capture

Aquifers are commonly depicted as underground reservoirs that replenish thanks to recharge (infiltrations from rainfall and river losses), constituting a "renewable resource". According to this view, groundwater can be managed sustainably as long as pumping remains below the recharge rate. However, it should be observed that under natural conditions the average amount of inflows is equal to the average outflows to springs, rivers, wetlands and other users downstream in the river basin. Particularly, groundwater outflows are essential during dry seasons or periods of droughts as the main component of the base flow of many rivers.

In dynamic conditions, for a given pumping rate, once the new steady state is reached, the amount of abstracted water corresponds to a reduction in discharge (e.g. less water flows to rivers and springs) and/or a rise in recharge of the aquifer (e.g. more water infiltrates from the river bed). The sum of these two terms can be referred to as "capture" (Fig. 2) [39,40]. Thus, pumping clearly results in a reduction in surface water flows. Capture is mobilized through a necessary groundwater table drawdown that depends of the intensity of pumping. Once pumping stops, the replenishment of the aquifer will continue to impact surface water bodies until the initial level of groundwater is attained again. In other words, there is a delayed impact of pumping on surface water resources [41].

However, the dynamic equilibrium is not attained in some situations and the groundwater table continuously drops. It is the case when the pumping rate is too high to be compensated by the maximum capture or when a new dynamic equilibrium takes a long time to be established. Stock depletion is usually identified as groundwater "mining" or "non-renewable" groundwater consumption [42,43], that has been referred to as "black water" [1], and linked to intergenerational equity issues associated with sustainability. Nevertheless, an additional effect of this pumping rate is that, in the case pumping stops, the replenishment of the aquifer will take more time to compensate for the large stock depletion and a delayed continuous capture of surface water flows will take place.
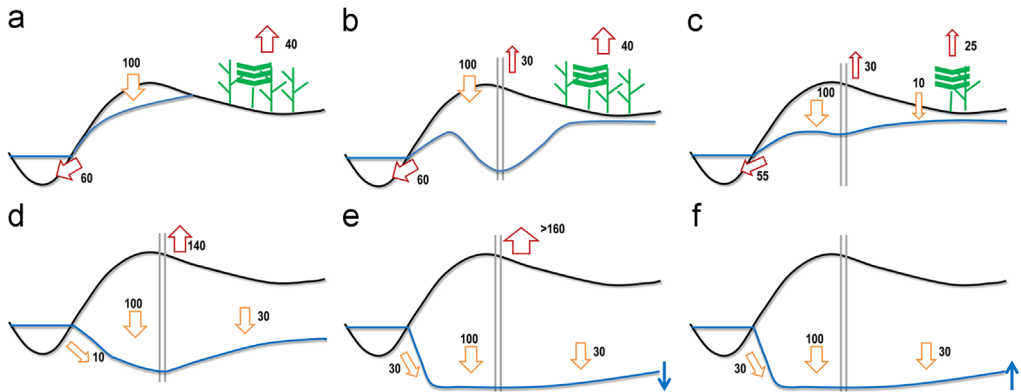
Fig. 2. Dynamics of capture mobilization and temporal consequences of groundwater pumping (adapted from [41]). (a) Natural state. Recharge feeds a river stream and a wetland. (b) Transient state. Level drops in the vicinity of the well and no impacts on river and wetland are noticed. (c) Steady state 1. Pumping (30) equals capture (reduction in discharge 5+15 and increase in recharge 10). (d) Steady state 2. Pumping (140) equals capture (reduction in discharge 60+40 and increase in recharge 30+10). (e) Maximum capture (160) is exceeded. Continuous consumption of the stock takes place. (f) Pumping stops. The replenishment of the aquifer implies a continuous impact on surface water.

This sustainability issue should be considered if surface water capture can be mobilized to replenish the aquifer, which is the case in the Guadalquivir river basin. Thus, in the consideration of WF_{blue_ground}, we distinguish a fraction that currently consumes surface water resources and a fraction that will impact water availability in the long run through stock depletion and future capture.

To obtain an estimation of abstractions from the aquifers' stock from the data presented for each of the sixty groundwater bodies in the draft Hydrological Plan [19], two cases are considered. When abstractions are reported to be higher than total inflows (recharge), the consumption of the stock is assumed to be the difference between the two values. When inflows are higher than abstractions and a continuous decline of level is reported (indicating a transient state: capture has not been fully mobilized), stock consumption is assumed to be half of the total abstractions. The other half is linked to a current consumption of surface flows. Additionally, the WF from groundwater stock has been considered to be linked entirely to agriculture.

2.3. Reference year

The evolution of the WF on the period 1997–2008 is only presented for agriculture. For the rest of the results (other sectors and detailed results in agriculture), the reference year is 2008. This year presents an average rainfall, which allows presenting "normal" conditions. However, because of the previous drier years, many management districts endured restrictions in water allowances (factor *drought*) in 2008. Thus, when the results for this year are presented to obtain a view of the situation independently from irrigation water restrictions, the factor *drought* is not considered. Moreover, the majority of data from the draft Hydrological Plan [19] have been obtained around this year.

2.4. Balance of the green and blue water consumption at basin scale

An overview of the relative weight of the green and blue WF (i.e. human appropriation of water) and ecosystems' water consumption at basin scale is obtained through the integration of these values within a hydrological balance of the basin (Table 1). The average repartition of rainfall between total run-off generation and evapotranspiration (i.e. green water) is obtained from the GRBA [19] and we use the values

Table 1
Repartition of rainfall between run-off and evapotranspiration and green and blue water consumption.

Rainfall	Run-off		Evapotranspiration
507 mm year^{-1} [a]	96 mm year^{-1}		411 mm year^{-1}
100%	19%[b]		81% [b]
28,850 Mm^3	5480 Mm^3		23,370 Mm^3
	Blue WF (without WF_{ground} from stock)+blue water flows		Green water (agriculture, pasture, forests)

[a] For the year 2008.
[b] According to [19].
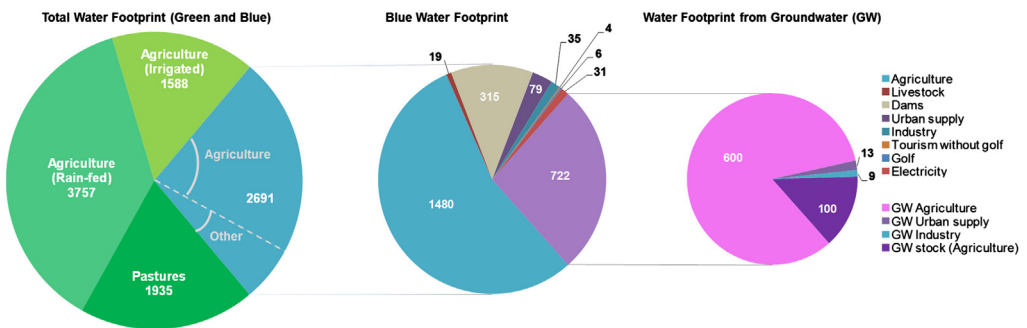
Fig. 3. The total water footprint (Mm^3) of the Guadalquivir basin, distinguishing green and blue (surface and ground water) water footprints.

of precipitation and WF for the reference year (2008) without water allowances restrictions, on the following basis:

- Total run-off is the sum of the blue WF (without WF_{blue_ground} from groundwater stock) and the remaining water flow running along the streams and recharging groundwater bodies.
- Evapotranspiration equals the sum of the green WF of agriculture on the whole year (cropping and non-cropping seasons), pastures and forest ecosystems. This allows estimating forest consumption.

On the basis of the hydrologic model BalanceMED applied to an area of the "Sierra Norte de Sevilla" [44], we assume that green water consumption during the non-cropping season amounts to 40% of green water consumed by agriculture on the whole year. Even if this model was applied to a small area of the Guadalquivir basin, this value can be introduced as a first approximation. This term is not included in the general approach of the green WF of agriculture (Section 2.2) in line with current standards on green WF calculation, which consider only the crops' growing period [1]. This point is discussed further in Section 4.1.

2.5. Economic value of irrigation water

For the purpose of this study, only the valuation of blue water for the agricultural sector is considered in detail. The apparent water productivity (*AWP*) is expressed as the ratio between market value (real € (year 2000) t^{-1}) and virtual water content (*CWC*/yield in m^3 t^{-1}) of the different crops. Annual national crop prices are obtained from the Statistical Yearbook of Agriculture [45]. Monetary estimation of the value of other uses (human and environmental uses) is not presented because of the difficulty to embody them into a single indicator. In Section 4.6, more considerations on the value of

water for the different uses are presented, particularly in relation to the reallocation of water resources.

3. Results

3.1. Synthesis of the total water footprint for the Guadalquivir river basin

The WF of the different economic sectors within the Guadalquivir basin for the year 2008 is summarized in Fig. 3. Overall, agriculture represents the largest WF, with 95% of the total WF or 75% considering only blue water. Evaporation from dams is also important since it comprises 11% of the blue WF, which surpasses by more than 100 Mm^3 the sum of the blue WF of all the sectors except agriculture. Sectors such as tourism and golf comprise a much lower share of the blue component ($<1\%$). In relation with the origin of blue water, around 25% (720 Mm^3) of the blue WF is from groundwater, almost entirely associated to agriculture. Groundwater constitutes around one third of the total blue WF of agriculture but represents only 26% and 16% of the total WF of industry and urban sectors respectively. Abstractions from the aquifers' stock, i.e. potential future capture of surface flows, amount to 100 Mm^3 (14% of the WF from groundwater for agriculture), with 73 Mm^3 referring to abstractions in excess of recharge and 27 Mm^3 pumped from aquifers presenting head drawdown (see Section 2.2.4).

3.2. The water footprint of agriculture and its evolution over time

Between 1997 and 2008 the total WF (green and blue) of agriculture production ranged between 4050 Mm^3 (year 1999) and 7230 Mm^3 (year 2001). These variations are mainly ascribed to the irregular pattern of rainfall within the basin, which has a high influence on the green WF (Fig. 4). During the period, 69% of mean annual agricultural WF in the Guadalquivir basin was green and the
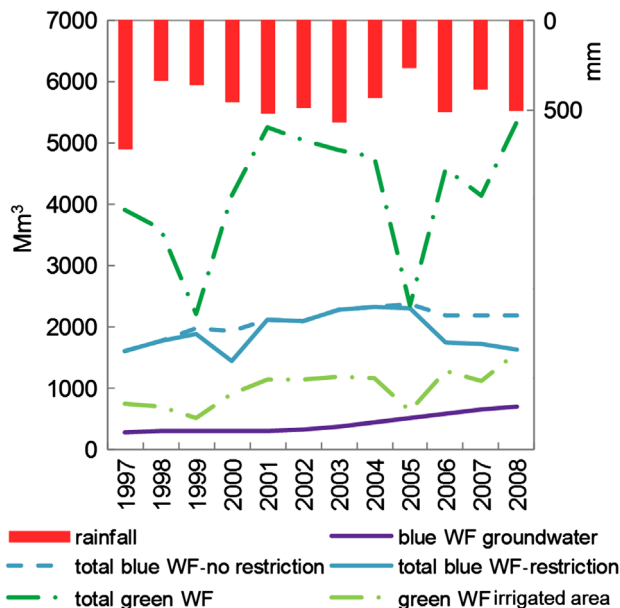

Fig. 4. Evolution of rainfall (mm, right axis) and the agricultural water footprint (Mm^3, left axis) by origin of water over the period 1997–2008.

remaining 31% was blue, including both surface and groundwater. Overall, olive groves consumed the largest proportion of green and blue water with 74% and 31% of the total WF respectively.

Two scenarios are considered for the blue WF: including or not the restrictions imposed through the factor *drought*. It allows distinguishing conjectural situations (droughts) from the general evolution of the potential WF governed principally by the evolution of the irrigated area. In reality the WF is situated between these two values, since doubts can be raised on the real application of the normative
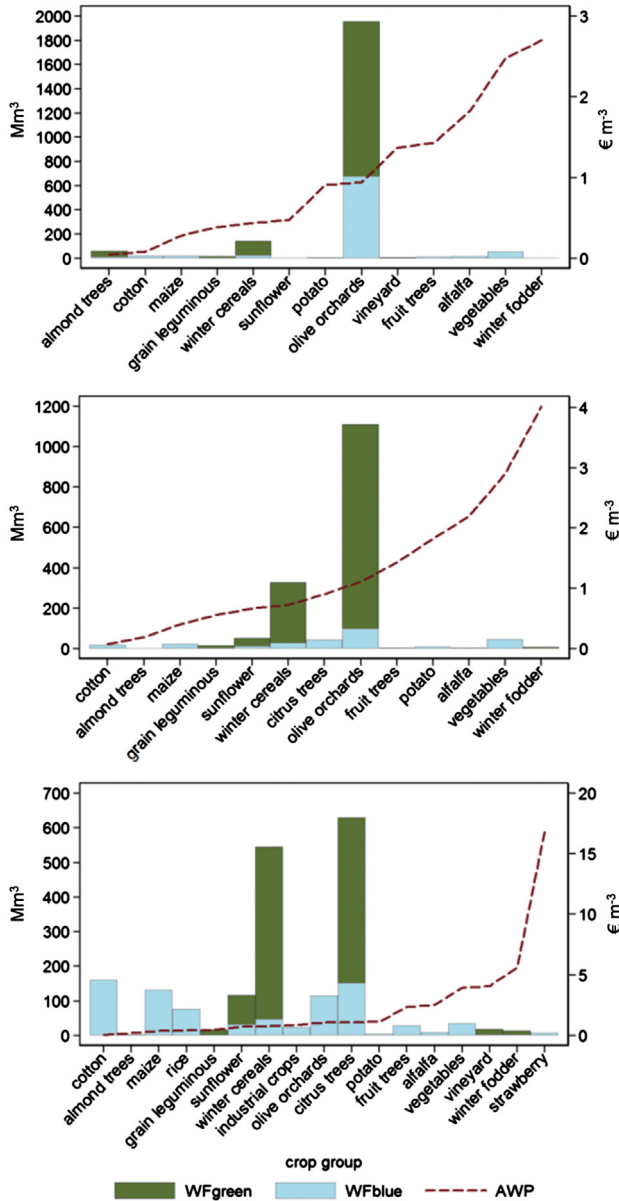

Fig. 5. Water footprint (WF in Mm^3, left axis) and apparent water productivity (*AWP* in € m^{-3}, right axis) by crop category and basin section for a normal climatic year (2008) and without water allowance restrictions. (a) upper section of the Guadalquivir basin. (b) middle section. (c) lower section.

restrictions. There has been a general rise in the WF until the year 2005. After, on the period 2006–2008, the WF decreases for both scenarios. Indeed, even without considering the normative irrigation restrictions, the effect of the low rainfall of 2005 has been a decline in the area irrigated from surface water, potentially because farmers preferred to secure the amount of water delivered to a more reduced area. Meanwhile, the WF from groundwater rose from 290 Mm^3 in the year 1997 to 700 Mm^3 in the year 2008. This increase is mainly ascribed to the expansion of irrigated olive orchards particularly over the last years (120 Mm^3 in 2002 to 490 Mm^3 in 2008).

A more detailed view by section of the basin (Fig. 5) shows that in the upper part of the basin the agriculture WF presents an average value of 2430 Mm^3, comprising 26% of blue water. This section is dominated by olive groves, both under rain-fed and irrigated conditions. The olive WF reaches about 1570 Mm^3 and 415 Mm^3 of green and blue water, respectively. In the middle section, the average WF is 1560 Mm^3 (65% attributed to olives), 17% being blue water. The lower part of the basin presents an average WF of approximately 1960 Mm^3, comprising green and blue water in similar magnitudes with 55% and 45%, respectively. The crops with a higher weight in the blue WF in this area are cotton (230 Mm^3), rice (200 Mm^3) and maize (100 Mm^3).

Concerning the origin of blue water (Fig. 6), the upper section presents an increase in WF_{blue_ground} of more than 170% between 2002 and 2008, with 210 Mm^3 linked to olives and 25 Mm^3 for the rest of the crops in 2008. The consumption of the groundwater stock occurs principally in this part of the basin (60%). In the middle section the share of groundwater is more limited. The highest WF associated to groundwater is located in the lower section, with a value of 410 Mm^3 (60% of total WF_{blue_ground}). The same as for surface water, there is more diversification of the crops irrigated from groundwater in the lower part, with only 57% of the WF linked to olive. However, for all the sections of the basin, and both for surface and groundwater, the share of olives WF has increased over the study period.

Even if part of the groundwater abstractions comes from aquifers' stock, mainly in the upper stretch of the basin, the major part of the increase of WF_{blue_ground} implies a higher pressure on surface water and associated ecosystems through capture. While the increase in the upper section is clearly linked to the extension of irrigated olive groves, the more intensive use of groundwater in the lower section can be partly explained by a reduced availability of surface water flows in the last years of the study. Since the conjunctive use of surface and ground water is common in this area [32], these figures might be linked to a greater use of groundwater to temporarily compensate for surface flow reductions. However, the drop in WF from surface water as presented in Fig. 6 may be exaggerated as the restrictions for the year 2008 might not have been fully operant.
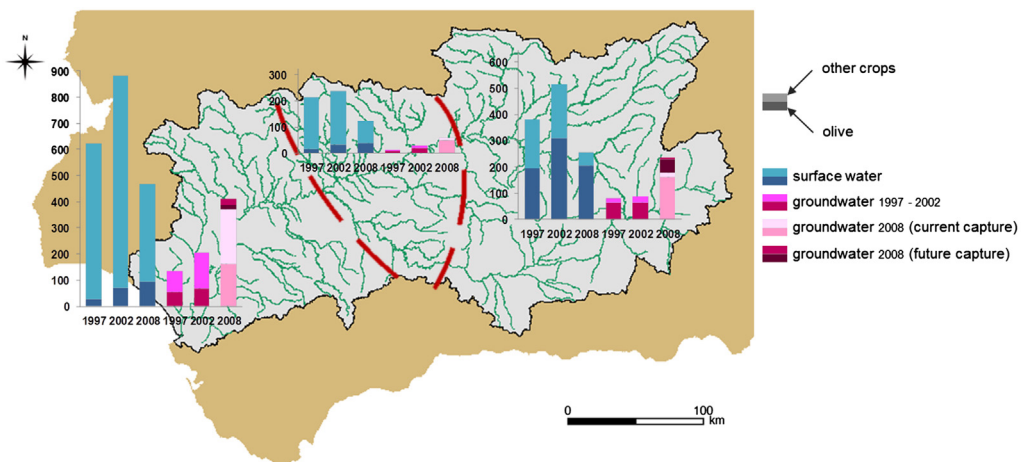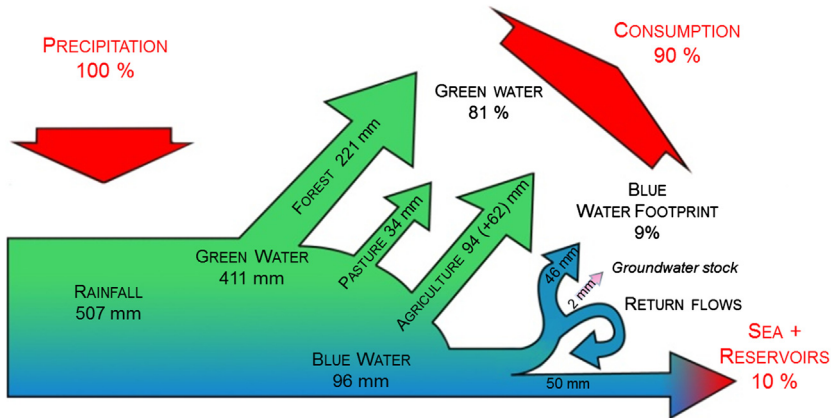

Fig. 6. Localization of the blue water footprint (Mm^3) by section of the basin and by origin of water (surface or groundwater) distinguishing olives water footprint. For the years 1997 and 2002, it was not possible to estimate the share of groundwater from stock consumption (future capture).

Fig. 7. The water footprint within the hydrologic cycle (adapted from Salmoral et al. [13], inspired by Falkenmark [46]), for a normal climatic year (2008) without irrigation allowances restriction. The first value of the water footprint of agriculture corresponds to the consumption during the growing period and the second value to the rest of the year.

3.3. Economic value of the blue water consumed by agriculture

Between 1997 and 2008, 40% of the blue WF belongs to crops with an *AWP* less than $0.40 \, € \, m^{-3}$, mainly cotton, rice and maize. Crops generating more than $1.50 \, € \, m^{-3}$ only account for 10% of total blue WF. These are principally open air vegetables, vineyards, winter fodder and strawberry. For the reference year (2008), in the upper part of the basin, olive presents an *AWP* of $0.9 \, € \, m^{-3}$, while for vegetables and winter fodder it reaches a value of 2.5 and $2.7 \, € \, m^{-3}$ respectively, although their blue WF is minimal (Fig. 5). In the middle part, *AWP* of olives is $1.1 \, € \, m^{-3}$ and vegetables ($3.5 \, € \, m^{-3}$) and winter fodder ($4 \, € \, m^{-3}$) again present the highest values. Cotton has an *AWP* of only $0.1 \, € \, m^{-3}$. In the lower section, although cotton, maize and rice are the largest blue water consumers, their *AWP* is less than $0.4 \, € \, m^{-3}$. Strawberries reach the highest productivity of blue water ($16.9 \, € \, m^{-3}$), followed by winter fodder ($5.6 \, € \, m^{-3}$) and vineyard ($4.1 \, € \, m^{-3}$). This confirms that the largest proportion of blue water resources is allocated to produce low value crops in the whole basin.

3.4. Integration of water footprint within the hydrological cycle

Throughout the hydrological cycle more than 80% of the rainfall turn into green water and only 20% are available in rivers and aquifers as blue water (Fig. 7). The majority of green water is consumed by forests (54%), while the direct human appropriation of green water (WF of agriculture and pastures) represents 46%. Regarding blue water, 50% of the total run-off is consumed annually (blue WF) and the other half partly discharges into the ocean, after contributing to sustain the ecological functions of aquatic ecosystems on its way to the river mouth. A fraction is also kept in the reservoirs to meet future demand. This general representation corresponds to a year with average climatic conditions. Depending on annual conditions, both total amount of rainfall and repartition between evapotranspiration and flow generation can vary significantly.

4. Discussion

4.1. The water footprint as human appropriation of water resources: distinguishing environmental and human water consumption

The WF has been introduced as an indicator of the appropriation of water resources by humanity (i.e. water consumed by ecosystems is not a WF) [1,47]. In a broad sense, this appropriation could be

understood as the consumption of water resources that generates value for the humanity. Off-stream blue water uses can generally be directly ascribed to the related human use, since water is withdrawn from streams and aquifers to a specific destination. However, the assignation of green water is more complex as, in parallel to human activities, land uses associated to green water consumption sustain ecosystems. The distinction between (human) WF and ecosystems consumption we proposed relies on the fact that for instance agricultural systems diverge from the initial "natural" land use and the evapotranspiration can be associated entirely to the WF of crops, even if agricultural ecosystems are valuable beyond the only perspective of crop production. According to this view, the green water consumed during non-growing season should logically be included in the green WF of agriculture, as fields cannot be considered more "natural" during this period. However, our main approach considers only the WF in the growing period, in line with the traditional methodology of the WF [1]. On the contrary, forests are considered as "natural" land use, even if direct economic activities are associated, like lumber or papermaking industries [48]. Pastures were also considered to be a land use associated to a human activity.

The consideration of ecosystem services [49] could extend this debate, since they could be considered also as "human appropriation". Van Oel and Hoekstra [48] suggest that, in the case of forests, a valuation of ecosystem services could allow allocating the evapotranspiration to the different functions of forests, based on the value factor, which consists in attributing the amount of the WF according to the relative monetary value of the different outputs [1,12]. However, this remains a conceptual discussion so far. Finally, the apparently simplistic distinction between "natural" land use and human activities proposed for green water is in line with the current developments of the WF and with our objective to present a general overview of the integration of the WF within the hydrologic cycle.

The value of forests' evapotranspiration was indirectly obtained as the difference between total evapotranspiration and green water consumption of all other land uses, i.e. the errors in these values are aggregated. The resulting consumption of 5300 m^3 ha^{-1} is slightly higher to other estimates (5100 m^3 ha^{-1} in average Spain [50]). Since groundwater tables are generally deep in the region and direct groundwater pumping by tree roots are negligible, forests are not consuming blue water. An exception would be the Doñana region (Guadalquivir river estuary), where eucalyptus plantations have been reported as a factor of groundwater depletion [51].

4.2. Implications of the water footprint as an indicator of consumptive use

Following the definition in terms of water appropriation, the blue WF indicator computes only water consumption, i.e. the share of withdrawals that is not delivered back into the basin to be re-used and generate value for other users or the environment [1], while traditional water planning focuses more on regulating total water withdrawals. The point is not to switch from an indicator to another but to promote the use of the WF as a complement to total water use. For instance, excessive withdrawals can impact a river stretch but cannot be considered as a definitive depletion of resources for the basin. This approach traditionally implies computing the evaporated water as the value of the WF. The efficiency of water use in the different sectors, which is commonly defined as the ratio between consumed and applied water, has been considered within this perspective. While this can be a valid estimation at basin scale, a more local study should assess carefully the destination and reusability of return flows (e.g. if they end in a saline aquifer or the sea) to include them or not in the WF [52,53]. As part of the return flows is necessarily "lost", our estimation underestimates the real WF.

Moreover, focusing on WF would promote an alternative view of several issues such as improving the efficiency of water application, through for instance the switch from traditional surface irrigation system to drip irrigation. This operation will potentially reduce water withdrawals; however, the WF will remain the same or even rise if return flows were initially re-used downstream [54]. In the same way, wastewater reuse potentially contributes to increase the WF if this water was previously delivered back to the basin to sustain downstream uses. The opportunity to develop these kinds of solutions should therefore be assessed carefully through a detailed water accounting,

for instance on the basis of the method proposed by Molden et al. [53], who introduced the indicator of "water depletion", which is basically the same as the WF.

4.3. Calculation of blue water footprint of agriculture in comparison with other studies

Green CWC is usually obtained from formulae or software with the input of only physical data (e.g. rainfall, soil properties, temperature). In the case of blue water, as stressed in Section 2.2, there are numerous factors (climatic, economic, agronomic, among others) affecting the actual application of irrigation water by farmers. In many arid or semi-arid areas, i.e. where irrigation usually takes place, water demand exceeds water availability, even for humid years. Yet, since data on real water application are not always available and may lack of relevance, WF accounting usually does not introduce this data and bases blue WF calculation on the assumption that CWR is fully met thanks to irrigation water. This is not the case for the Guadalquivir basin and we calculated the agricultural blue WF considering irrigation water allowances and normative restrictions during drought periods. Even if there are great uncertainties on their compliance, potential errors remain low in comparison with assuming that CWR is fully satisfied. Only considering olives, with a CWR of 4000 m^3 ha^{-1} in a normal year, the total WF of agriculture would have reached a value of around 50% higher than the baseline estimate for 2008.

4.4. Benefits of groundwater use and methodological challenges

The lack of specific data on the origin of the water usually limits the possibility to lead to a detailed assessment of the WF from groundwater. Here, data on groundwater irrigated areas were available for several years. The constant availability of groundwater constitutes a major benefit since farmers are able to irrigate in case of surface water shortage, not affecting yields. Thus, with the exception of olive groves (deficit irrigation strategy), CWR were considered as satisfied, even if the cost of pumping may imply some restriction [55]. Since yield data do not differentiate the value depending on the origin of water, a higher CWC implies that the calculated virtual water content of the crops (CWC/yield) is also higher (i.e. the water productivity is lower) for groundwater irrigation. This is not the case in reality because of the higher yield allowed through groundwater use. In addition, the reliability of groundwater allows farmers to grow crops with higher market value, but more vulnerable to droughts.

4.5. Sustainability assessment

After WF accounting, a WF assessment should ideally include a sustainability assessment [1]. The Guadalquivir river is deeply affected by human activity, especially in relation with the necessity to deliver water to farmers during summer months for irrigation. It is a highly regulated watershed and during the low flow season (May–August), river flows come mainly from reservoir discharges for irrigation. We showed that on average around half of the blue water resources are consumed. This ratio is based on an average climatic year, during drier years less blue water flow would be generated. In addition, it does not mean that half of the flows reach the sea, since water is kept in reservoirs for the following years. An idea of the situation of water resources in the basin can be obtained through the results of the assessment of water bodies' status according to the EU WFD process. They are generally in poor status particularly within the lower stretch of the basin. Thus, we can consider that there is a general overuse of water resources in the Guadalquivir basin, as the current pattern of water use substantially impacts the quantitative and qualitative state of water resources.

It could be tempting to undertake a separate assessment for the WF from groundwater, since groundwater resources are sometimes seen as additional resources managed at the scale of the groundwater body. However, as described previously, the major part of groundwater abstractions have a direct impact on surface water flows. Only the depletion of the aquifers' stock constitutes an additional contribution to the basin water resources for now. Moreover, in addition to the direct issues associated to rising pumping costs because of level drawdown, sustainability of groundwater stock consumption should be addressed relatively to the long-term impacts on surface water (future capture). Particularly, groundwater-based irrigation of olive groves within the upper stretch constitutes an additional pressure

on the water resources of the whole basin [34], affecting potentially all preexisting users and the environment as a higher WF makes it harder to implement ecological flows downstream.

4.6. Water productivity: towards the reallocation of water resources?

A common argument to promote olive groves irrigation is that it presents a higher productivity than many other irrigated crops located downstream, which is confirmed by our results (Fig. 5). Other crops, such as strawberry or vegetables, are also commonly presented as opportunities because of their high *AWP*. It should be reminded that *AWP* constitutes an estimation of the average value generated by the totality of the current use of water. What should be considered for the reallocation of water is the marginal value [56]. For instance, under repeated situations of overproduction of olive oil, it could be considered that the increase of production allowed by irrigation makes the price drop (i.e. negative marginal water productivity). However, the presented values of *AWP* can be considered as a first overview of the crops that are generating more economic value in the Guadalquivir basin, as it appears clearly that crops, such as cotton or cereals have a limited contribution to the local economy.

Meanwhile, new uses should not result in a rise of the overall basin WF. Reallocation of water rights should be promoted and be accompanied by an assessment of potential social and environmental impacts, with adequate compensation. This should be taken into account for the development of thermo-solar plants, which could imply an additional WF of 8 Mm^3 in the next years [19].

5. Conclusions and recommendations

One of the main innovations of the present study is to have included the green and blue WF within a water balance at the scale of the Guadalquivir basin. It constitutes a first overview of the repartition of water resources between human activities and the environment, in line with the definition of the WF in terms of "water appropriation by humanity"[1]. The green WF amounts to 190 mm, i.e. 46% of total green water consumption. Concerning blue water, the total WF reaches half of the blue water flows generated in a normal year, which means a high pressure on aquatic ecosystems because of rainfall variability and because much of this water is kept in reservoirs along the river course to meet future demand or can replenish aquifers.

A view of the WF by economic sector reveals that the highest share is related to agrarian activities (agriculture and pastures) as expected. In the case of green water, it shows how agriculture accesses to water through rainfall thanks to land occupation. In this respect, future developments of the WF methodology should refine its formulation as human appropriation of water. Agricultural areas have an ecological and landscape value that cannot be reduced to the direct benefits obtained from yields. Instead, the view of a continuum between human and ecosystems water consumption may be more relevant. The traditional consideration of green water consumption only during the cropping period is an additional evidence on how water footprinting has focused on water as an input for material production so far, while a more integrated view would integrate green water consumption over the whole year.

Agriculture, without the dams WF, represents also 80% of the blue WF. The attractiveness of irrigation comes from the substantial increase in profitability allowed by blue water. However, many users benefit from this resource and environmental and social conflicts are recurrent in a context of high climatic variability. The state of the water resources presented in relation to the EU WFD clearly reveals the need for a reduction of the current WF to relieve the pressure on the environment and to improve water quality. Nevertheless, some common solutions to address the "water crisis" – rising efficiency through irrigation modernization and wastewater reuse [19] – should be introduced with caution. In many cases, these actions result in an increase of the WF (for instance through the shift to more water-intensive crops or irrigated area development), leading to the consumption of resources committed to other users downstream. In this situation, rising efficiency can hardly be understood as demand management since the WF increases. On the contrary, it allows retaining water upstream, making it available there, just like a dam.

Effective demand management would improve the possibilities for new water uses that potentially generate more value than agriculture, such as thermo-solar plants or tourism, to obtain water rights

from current users. This is also valid within the agricultural sector for the more productive crops. Groundwater does not constitute additional resources to compensate for surface water failures and should be fully integrated in this process. Its use, amounting to 720 Mm^3 in 2008, reduces surface water availability now and/or in a more or less near future, as we have estimated that 86% corresponds to current capture.

Overall, reallocation would suppose a small share of current use and it can be considered there is no lack of water in the basin since better governance and cooperation could ensure that reallocation and restriction policies are set up with a better sharing of benefits from blue water and adequate compensation of their consequences. Under the possibilities offered by a globalized market, additional food and feed products could be imported and new water users would be incorporated into the economy of the region.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments

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