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Article

Estimation of the agricultural water footprint of DR 011, upper Lerma River

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Abstract

In the search for indicators that help measure the impact of human activities on the environment and natural resources, there is one that is very useful as an indicator of demand for global water resources. Estimating the water footprint of agricultural production allowed the identification of crops that can reduce it in favor of increasing water use efficiency. Hoekstra *et al*. (2011) methodology was used to estimate the water footprint of agricultural products in Irrigation District 011. It was found that of 14 crops in the district, in the average total water footprint in the irrigation modules (dam^3 t^{-1}), those of peanuts, beans, and nopal report the highest levels (1.7, 1.6, and 1.8, respectively), while those of lettuce, husk tomato, and carrot crops are the lowest (0.15, 0.29, and 0.25, respectively). Of the water footprint of total agricultural production (dam^3), it was observed that corn participates with 43.4%; however, it accounted for 52.8% of total production. The peanut and alfalfa crops in module 05 are economically unaffordable, with high blue water costs per tonne ($8 623.00 and $11 914.00); nevertheless, they occupy 1% of the planted area. The variation of the water footprint of crops among the irrigation modules obtained helps identify the agricultural practices that contributed to increasing yields and optimizing the application of irrigation, consequently providing greater economic benefits to producers.

Keywords:

efficiency, scarcity water, virtual water.

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Introduction

For decades, debates about the impact of human activities on the world's water resources have increased, creating enormous challenges for inhabitants and for all different water users, intensifying where the consequences of climate change begin to manifest themselves in an unobjectionable way (Bernauer and Böhmelt, 2020). The international conference on water and the environment in Dublin, Ireland, produced the 'Dublin Statement', which constituted the main element of freshwater problems (WMO, 1992).

It is worth remembering two of the four guiding principles of the conference that are relevant to the study at hand, which does not mean that the other two are less important. This is guiding principle number 1 and number 4 (WMO, 1992): principle number 1, 'freshwater is a resource that is finite (2.5% of the 1.4 billion cubic kilometers of water on the planet) and vulnerable, essential to sustain life, development and the environment', and guiding principle number 4, 'water has economic value in all its various competing uses for which it is intended and should be used be recognized as an economic good'.

These two principles, in addition to unequivocally admitting the importance of water for life and all human activities and the environment, point out that, due to its scarcity and multiple uses, it must be recognized as an economic good; therefore, economics and its principles are useful in improving its use.

Thanks to the constant dialogue on the problem of water resources and to the scientific and technological advances that have been developed around the water issue, it has been possible to understand the processes that take place to quantify the availability of the resource throughout the water cycle, the institutions involved in the regularization of the exchanges between the ecological and socioeconomic systems and the precursors of the apparent scarcity of water have been identified, and methodologies have been proposed and applied to identify the state of multilevel water governance (OCDE, 2015).

In recent decades, concepts and indicators have been developed that have helped measure the impact of human activities on the environment and natural resources. These include the ecological footprint, the carbon footprint, the virtual water, and the water footprint. The water footprint (WF) is a concept developed in analogy with the concept of ecological footprint, which analyzes the patterns of resource consumption and waste production of a given population (Hoekstra and Chapagain, 2006); the WF concept was introduced a decade after the concept of virtual water (Allan, 1994) in conferences of water experts by Hoekstra and Hung.

WF and virtual water (VW) are closely related (Chapagain and Hoekstra, 2004); VW is defined as the volume of water needed to produce a product or service; in addition to the physical water it can contain, it also includes the amount of water that has been required to generate said product or service (Oltra-Cámara and Jimenez-Honrado, 2018); for its part, the description of WF is the volume of water needed to produce the goods and services consumed by inhabitants within a geographic area, a river basin, or a country (Dan *et al*., 2021).

WF is presented as a marker of water use behind each product. The concept is used to assess water use along supply chains (Hoekstra, 2016), sustainability of water use within river basins (Abbasi *et al*., 2019), water use efficiency (Cao *et al*., 2021), equity in water allocation (Kumar, 2021), and dependence on water in the supply chain (Aivazidou *et al*., 2018). Hoekstra *et al*. (2011) mention that water in a basin should be allocated economically efficiently to different users, and each user should also use their allocated water efficiently.

WF has been used as a tool to assess and improve efficiency in water use and water resources management (Lathuillière *et al*., 2018); an advantage of using WF and VW approaches lies in giving meaning to the idea of transversality required in the implementation of a country's water policy (Pérez-Espejo *et al*., 2016), in such a way that some researchers call for the previous approaches be replaced by the VW and WF approaches (Bazrafshan *et al*., 2020) for the analysis of water resources management policies.

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There are three components of WF depending on the source of the water: green water footprint (rainwater), blue water footprint (freshwater), and grey water footprint (water quality); the latter refers to the volume needed for the assimilation of pollutants; together, these components provide a complete picture of water use by delineating the source of water consumed.

The economic benefits associated with a WF, in any of its components (green, blue, or grey), resulting from using water for a specific purpose must outweigh the total cost associated with this WF (Hoekstra *et al*., 2011). In the Lerma-Chapala river basin in Mexico, the scarcity of water and its growing demand for irrigation have caused crises of intermittent dry years since 1950 (Vargas-Velázquez, 2007); for this reason, great interest has been aroused in water resources in terms of quality and quantity in prolonged dry periods, since conflicts are generated in the region between users and water authorities due to the intense competition for water resources among the sectors that demand it (Fernández-Durán y Lloret-Carrillo, 2016).

The presence and increase of water scarcity, the growing competition for water between sectors, and the reduction of options in water resource supply strategies in the agriculture in the Lerma-Chapala basin motivated us to carry out this research on the blue, green, and gray WF of the agricultural production of Irrigation District 011, Upper Lerma River (DR 011) so that the results allow the identification of crops that can reduce their water footprint to strengthen the management of water demand and increase the efficiency of its use in agriculture.

Materials and methods

DR 011 is located in El Bajío Guanajuatense; it has 11 associations of irrigation users known as ‘irrigation modules’, which group 26 611 users; it has a total of 111 242.55 ha, of which 110 299.45 are irrigated (Rodríguez-Flores *et al*., 2019).

The study’s development was based on the application of Hoekstra *et al*. (2011) methodology for quantifying the water footprint of agricultural or forestry products. The methodology for calculating the WF was carried out in two stages. In the first part, the general scope of the evaluation was defined, and four basic steps were followed in order to provide clarity on the type of information needed and the sources of search.

First, DR 011 was defined as the study area to calculate the blue, green, and gray WF of agricultural production (Figure 1); it extends from the Solís Dam (Municipality of Acámbaro) to the area of influence of the Turbio River. The dams that supply the district are four storage reservoirs: the Tepuxtepec Dam, the Solís Dam, Lake Yuriria, and the Purisima Dam. Second, the scope of the research was limited, with the capacity to propose alternatives at the regional level that improve the water resources management policies of the study area.

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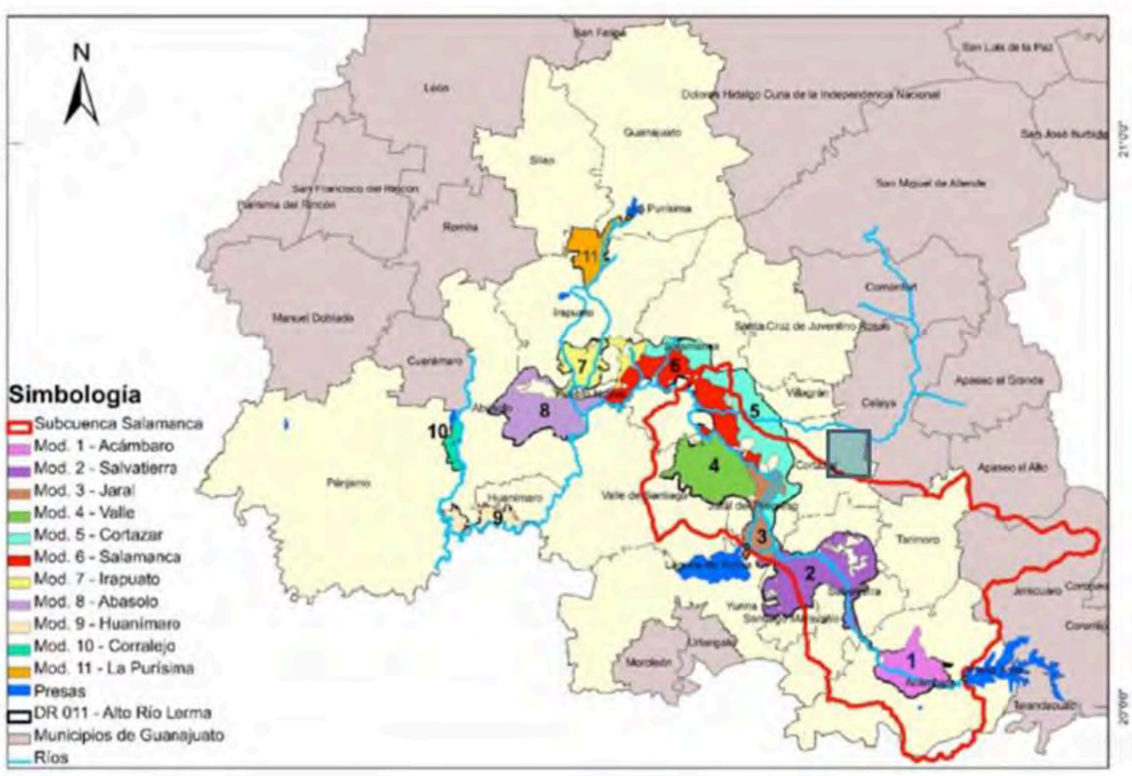
Figure 1. Location of Irrigation District 011 (Magaña-Zamora *et al*., 2017).



In the third step, strategies were defined for collecting primary information; the leadership of DR 011 granted facilitations for obtaining information on crop yields, irrigation programming, and agricultural production of each of the 11 irrigation modules that make up the district. The hydroclimatic information required for each of the modules of DR 011 (Table 1) was obtained with the help of the Aquastat database (FAO, 2022).

Table 1. Geographical location of irrigation modules of DR 011, Upper Lerma River.

Module		Latitude N	Longitude W	Altitude (m)
1	Acámbaro	20.08	100.77	1 846
2	Salvatierra	20.24	100.95	1 743
3	Jaral	20.33	101.03	1 729
4	Valle	20.42	101.14	1 718
5	Cortázar	20.47	101.02	1 730
6	Salamanca	20.58	101.19	1 715
7	Irapuato	20.62	101.35	1 717
8	Abasolo	20.51	101.46	1 700
9	Huanímaro	20.34	101.53	1 692
10	Corralejo	20.48	101.62	1 692
11	La purísima	20.8	101.36	1 749

Information from the Leadership of Irrigation District 011.

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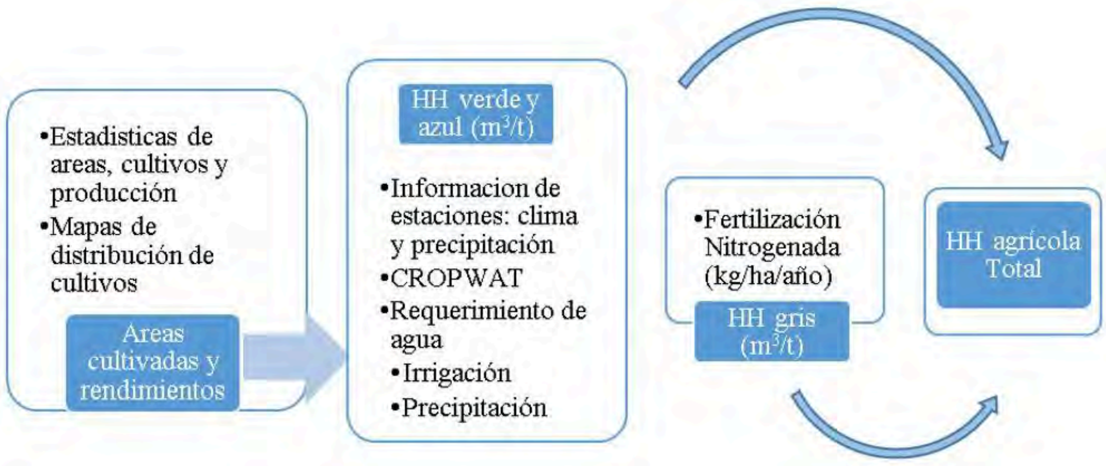
Finally, the reliability of the information was analyzed. After carrying out the basic steps, the information was organized into different groups, each containing the basic information for the study, the hydroclimatic information, and the economic aspects.

In the second stage, the WF of the process of the crops (agricultural water footprint) with irrigation from the surface supply sources of the 2021-2022 agricultural cycle was estimated, which is composed of the blue, green, and gray water footprint and is expressed in m^3 t^{-1} (Figure 2).

Figure 2. Methodology for calculating WF (Hoekstra *et al*., 2011).



The hydroclimatic information was used in the FAO Cropwat 8.0 software to estimate the evapotranspired blue water (ET_{blue}) and evapotranspired green water (ET_{green}), which are expressed in mm period^{-1} and with a ratio of 10 are converted into blue water used by the crop (CWU_{blue}, m^3 ha^{-1}) and green water used by the crop (CWU_{green}, m^3 ha^{-1}); finally, the blue component of a crop's water footprint (Eq1) ($WF_{crop,\ blue}$, m^3 t^{-1}) was calculated as the blue water used by the crop divided by crop yield (Y, t ha^{-1}). The green component (Eq2) ($WF_{crop,\ green}$, m^3 t^{-1}) was calculated similarly.

$$WF_{crop,\ blue}=\frac{CWU_{blue}}{Y}$$

Eq1.

$$WF_{crop,green}=\frac{CWU_{green}}{Y}$$

Eq2.

The grey component of each crop's water footprint ($WF_{crop,\ grey}$, m^3 t^{-1}) was calculated by multiplying the rate of nitrogen fertilizer application per hectare (AR, kg ha^{-1}) by the leach-surface runoff fraction (α) divided by the maximum allowable concentration (C_{max}, kg m^{-3}), minus the natural concentration for nitrogen fertilizer that is applied (C_{nat}, kg m^{-3}) and then divided by crop yield (Y, t ha^{-1}).

$$WF_{proc,\ gray}=\frac{(\alpha \cdot AR)/(C_{max}-C_{nat})}{Y}$$

Eq3.

α was considered to be 10% of the applied fertilization rate, as stated by Hoekstra *et al*. (2011). The maximum concentration allowed in surface water bodies was taken from the Mexican standard NOM-127-SSA1-2021, which indicates 10 mg L^{-1} (measured as N); the natural concentration was

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considered equal to zero due to lack of appropriate information, and the information regarding the rate of nitrogen application in crops was taken from the agricultural technical agenda of the state of Guanajuato (SAGARPA, 2015).

When the price of water to the user is below its actual economic cost, it usually results in inefficient use, as is generally the case in agriculture. To make an economic analysis of the surface blue WF for irrigation Botello-Aguillón *et al*. (2022) research was taken into account, where they found that, on average, the shadow price (the marginal productivity) of water from modules 02 and 05 of DR 011 was higher (26 times) than the irrigation fees paid by users; using the research values (Table 2), they were multiplied by the WF of each crop to determine the actual economic loss of the surface water that is consumed (extracted from the basin) in agricultural production.

Table 2. Shadow price of surface water for irrigation in DR011 (Botello-Aguillón *et al*., 2022).

	Shadow price of water (\$ dam^{-3})	
Cycle	M02	M05
A-W	1 284	1 371
S-S	2 084	3 872
Perennials	1 964	12 771

The total WF of a geographic area generates an economic tipping point; that is, it is economically unsustainable when water is not allocated and used economically efficiently. The benefits of a WF (green, blue, or grey) that result from using water for a particular purpose should outweigh the total cost associated with this water footprint, including the externalities and costs of water scarcity (Hoekstra *et al*., 2011).

DR 011 is sown in the autumn-winter (A-W) cycle, which lasts from October to November; harvests are carried out in February and March, and mainly wheat, barley, and vegetables such as broccoli and lettuce are grown. In the spring-summer (S-S) cycle, the sowing goes from March to April, and the harvests from September to October, and mainly corn and sorghum are grown. There are perennial crops, the main ones being alfalfa and asparagus. They are considered as second crops, after corn and sorghum, usually sown in May.

Results and discussion

Following the methodology described above, the blue, green, and gray components were obtained by crop in each irrigation module of DR 011 (Table 3). It should be noted that the evapotranspiration of water in catchment areas and conduction canals was ignored, and green and blue water incorporated into crops was not accounted for because, in the literature, it is considered to be between 75 and 80% (Hoekstra *et al*., 2011), which represents less than 1% of the water footprint with respect to evaporated water. The gray component of chickpeas is considered 0% because nitrogen fertilizer is not applied since the crop is usually sown under conditions of restricted humidity.

Table 3. Water footprint by component of each crop of DR 011.

	Water footprint components by crop		
	Blue (m^3 t^{-1})	Green (m^3 t^{-1})	Gray (m^3 t^{-1})
Alfalfa	298.7	478.5	30.4
Oats	935.1	140.7	166.2
Peanuts	1 055.8	535.5	89
Barley	722.9	66.8	149.6
Asparagus	1 015.2	1 345.3	85.9
Beans	1 116.8	279.7	200.1

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	Water footprint components by crop		
	Blue (m^3 t^{-1})	Green (m^3 t^{-1})	Gray (m^3 t^{-1})
Chickpeas	1 064.4	249.9	0
Lettuce	74.3	9.5	61.5
Corn-grain	85.3	321.7	211.3
Nopal	892.5	770.1	125
Sorghum-grain	68.2	352.8	249.9
Husk tomato	195.9	46.7	50.1
Wheat	626.4	60.5	391.5
Carrot	193.6	22.1	30.8

In a report on Colombian agriculture's water footprint that considers the gray footprint, the WWF (2012) reports percentages of the blue, green, and gray components of 7.1, 87.1, and 5.8%, respectively, unlike the present study where the percentages are 56.1, 31.5, and 12.4%, respectively; the difference between the percentages of blue and green WF may respond to the difference in rainfall.

Authors such as Álvarez *et al*. (2016) mention that the blue water footprint becomes more relevant with the lower occurrence of rainfall, which implies a greater demand for irrigation water; while Colombia presented an average annual rainfall of 1 293.1 mm, in Guanajuato, Mexico, the average annual rainfall is only 478.4 mm (Weather Spark, 2022).

When the climate phenomenon of La Niña occurs in winter and spring, a drought occurs regularly in central and northern Mexico. Lobato-Sánchez and Mejía-Estrada (2021) agree that this situation occurred in 2020 due to the fact that the phenomenon of La Niña persisted since the last quarter of 2020, causing the rainy season to be below its average value.

The relationship of gray WF in the studies is more limited, the different fertilization doses or lack of data are a possible cause of the differences. Arenas *et al*. (2020) found that, in the studied area, the proportions of WF in agriculture changed from 18% (blue), 78% (green), and 4% (gray) for a wet year (1 030.6 mm, in 2007) to 68% (blue), 29% (green), and 3% (gray) compared to a dry year (675.1 mm, in 2015).

By adding the water footprint components, the total WF for each crop by agricultural cycle and module for surface water was determined. The average total WF of 14 crops was estimated, of which peanuts, beans, and nopal crops reported the highest WF, while vegetables with lettuce, husk tomato, and carrot crops had the lowest WF (Table 4).

Table 4

Average water footprint of crops in the 2020-2021 agricultural cycle in DR 011.

Crop/ module	Water footprint (dam^3 t^{-1})										
	01	02	03	04	05	06	07	08	09	10	11
Alfalfa	0.4	0.7	0.5	0.3	2.4	0.7	0.4	1.1			
Oats	0.4	3.7		0.3	1.5		0.3				
Peanuts		1			2.9						1.1
Barley	0.7	1.3	0.9	0.8	0.9	1	0.9	1	0.9		1
Asparagus					2.5	1.5	3.3	2.6			
Beans		1.9			1.3						
Chickpeas	1.5	0.6	1.9	1.2	1.6		1.1				
Lettuce					0.1						
Corn-grain	0.7	0.5	0.6	0.6	0.6	0.7	0.6	0.6	0.6	0.5	0.7
Nopal						1.8					

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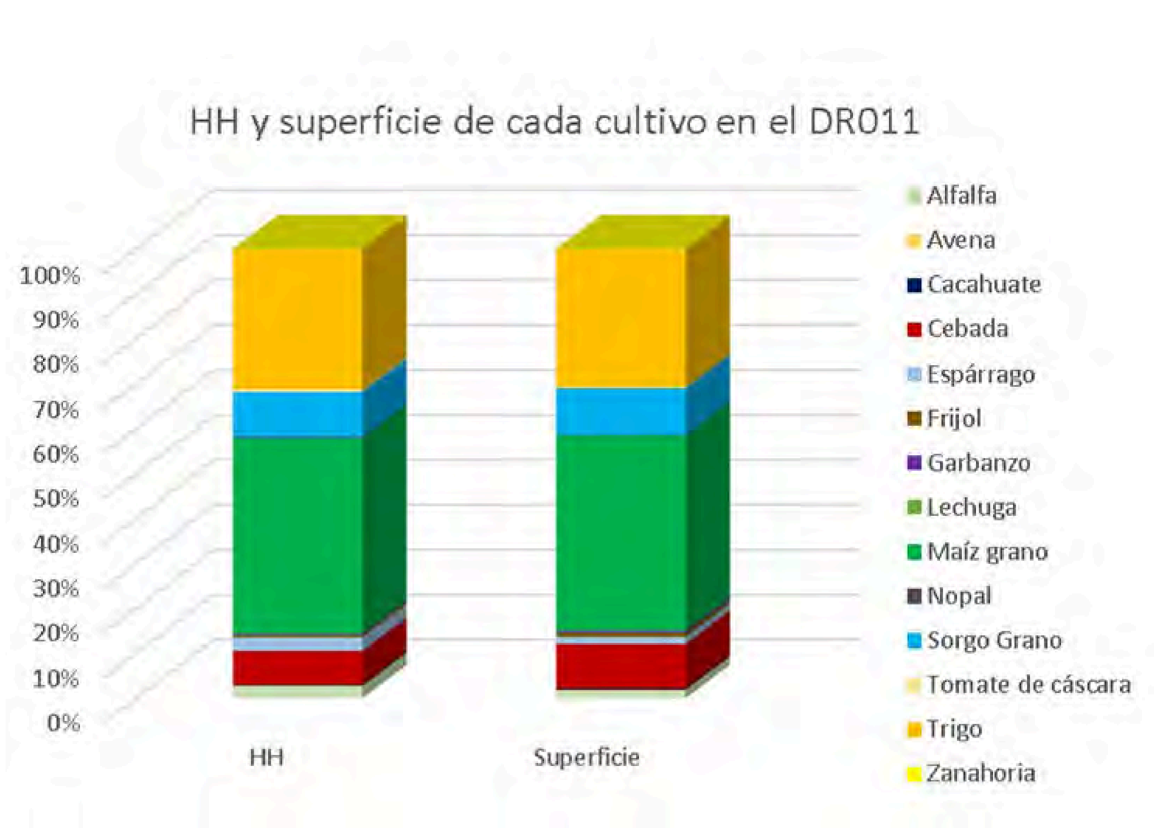
Crop/ module	Water footprint ($dam^3 t^{-1}$)										
	01	02	03	04	05	06	07	08	09	10	11
Sorghum-grain	0.6	0.6	0.6	0.6	0.7	0.8	0.7	0.7	0.6	0.6	0.8
Husk tomato	0.3										
Wheat	0.9	1.1	1.2	1.1	0.9	1.2	1.1	1.1	1.2		1.2
Carrot		0.2									

The results of the average water footprint of the crops of the agricultural cycle of the present research are related to Magaña-Zamora *et al*. (2017), who, for the same irrigation district, quantified the average blue WF of irrigation of dams and pumping and found that the crops that have the lowest blue WF are vegetables, represented by lettuce, carrot, and watermelon (21, 14, and 15 $m^3 t^{-1}$, respectively), while the highest values are in perennial crops, such as asparagus, alfalfa, and grass (1 235, 452, and 333 $m^3 t^{-1}$, respectively).

In the WF results of the total production of DR 011 and its sowing area (Figure 3), it was observed that corn and wheat crops have a high weight in terms of total WF, participating with 74% of the total, corn 43% and wheat 31%; nevertheless, the crops accounted respectively for 53% and 22% of the total production of DR 011, in contrast to lettuce, which represents only 0.007% of the total WF with only 0.04% of the total production.

Figure 3.Total water footprint of crops for the 2020-2021 agricultural year in DR 011 and its sowing area.



Corn, wheat, sorghum, and barley crops need large amounts of water due to their large surface area. These four crops alone use 94% of the area under gravity irrigation.

The relationship between the blue WF of crops and the shadow price of surface water obtained from Botello-Aguillón *et al*. (2022) in modules 02 and 05 was used to determine the value of blue WF

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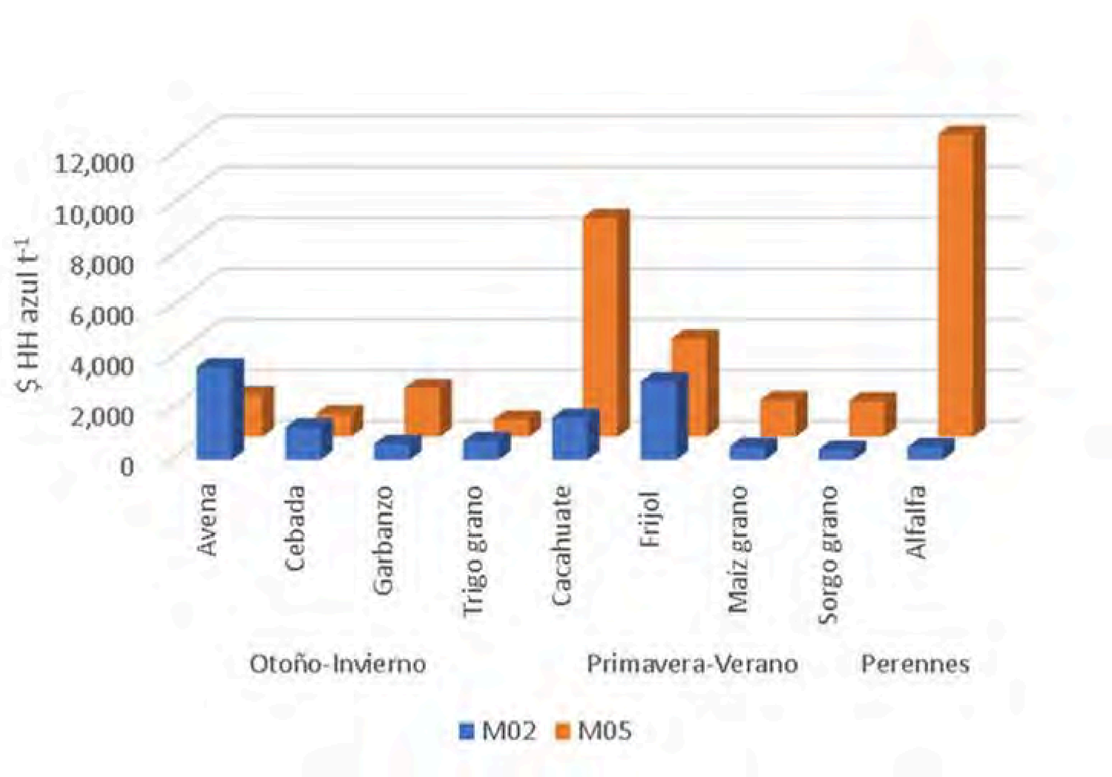
per tonne of each crop (Figure 4). Alfalfa, peanut, and bean crops are the most expensive in terms of blue water, mainly because they have low agricultural productivity compared to other modules. One of the characteristics of WF is that it is a spatial and temporal indicator.

Figure 4. Value of blue WF per tonne of M02 and M05 crops.



The low yield of these crops can be caused by negative, external, and temporary agents; therefore, an in-depth analysis of the possible causes is needed so that a strategy is implemented to help increase production and thus improve the economic benefits of the use of blue water.

Figure 5 shows the distribution of blue WF by crop in each module of DR 011, showing the weight of blue WF (dam^3) of the total production of wheat, corn, and barley crops, which together account for 85.8% of the total blue WF, with 51.3, 18.1, and 16.4%, respectively. Module 05: Cortázar, stands out as the one with the highest blue WF, coinciding with Magaña-Zamora *et al*. (2017), while module 10: Corralejo stands out as the one with the lowest blue WF; however, the latter is the one with the smallest sown area, with less than 1%.

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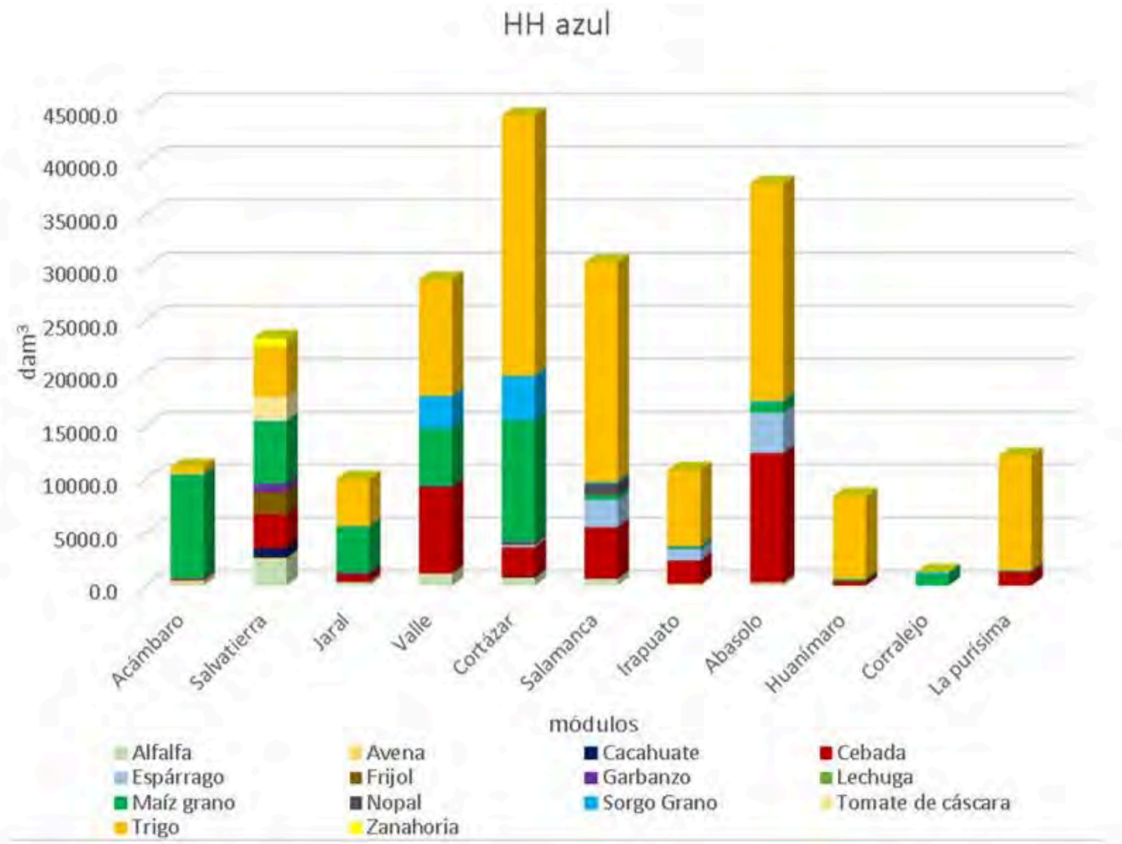
Figure 5. Blue WF of crops by modules of DR 011.



Research such as that by Mekonnen and Gerbens (2020) mentions that economic valuation must be integrated with the assessment of water footprints and virtual water flows to allocate water efficiently and in combination with virtual water trade, this will help avoid unsustainable water use.

Conclusions

Variation in the water footprint (dam^3 t^{-1}) among crops indicates changes in agricultural practices that can be identified to reduce the WF of crops with the highest values. The percentage of blue WF is important to identify the use of water employed for irrigation in agriculture; the blue percentage will be higher when there is less rainfall in the geographical area of study; the low productivity of crops causes an increase in blue and green WF.

Grey WF represents a considerable percentage (17%) in the accounting of the total WF; attention must be paid to the fertilization rates applied by users of DR 011; efficient use of fertilizers and pesticides can considerably reduce the gray component. Improvements in agricultural practices that contribute to increasing crop yields and those that optimize the application of irrigation will reduce the water footprint of each crop and consequently bring greater economic benefits to producers derived from better use of water. Water is an important resource in agriculture and it is essential to have measures that help contribute to its efficient use, especially where there is a scarcity of this resource, such as arid and semi-arid areas.

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