Environ Monit Assess (2023) 195:1532
https://doi.org/10.1007/s10661-023-12029-4

RESEARCH

Water footprint of irrigated rice in the state of Rio Grande do Sul, 2019/2020 crop

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Received: 8 September 2023 / Accepted: 23 October 2023 / Published online: 27 November 2023

Abstract Agricultural production is the practice that uses the most water on the planet, especially the irrigated agriculture, which represents a large part of this demand. As well as the quantitative issue, adequate quality is essential to meet the demands of the crop and its return to the water sources, in a way that does not cause damage to the environment. To measure this consumption, the expression "water footprint" emerged. The water footprint seeks to quantify the demand for water incorporated into products. This paper aims to determine the amount of water used to produce irrigated rice in six rice growing regions in the state of Rio Grande do Sul (RS), in the 2019/2020 crop. The mentioned regions are represented the municipalities of Uruguaiana (West Border), Dom Pedrito (Campanha), Santa Maria (Central Region), Camaquã (Internal Coastal Plain), Porto Alegre (External Coastal Plain), and Rio Grande (South Zone). Climate data from the analyzed regions, during the plant cycle, and productivity values in the crop in question were used. Values of 1187 $m^3\ t^{-1}$ were found for WB, 1347 $m^3\ t^{-1}$ for CA, 1058 $m^3\ t^{-1}$ for CR, 783 $m^3\ t^{-1}$ for ICP, 1115 $m^3\ t^{-1}$ for ECP, and 1066 $m^3\ t^{-1}$ for SZ. For the state of Rio Grande do Sul, an average water footprint was obtained in the 2019/2020 crop of 1093 $m^3\ t^{-1}$.

Keywords Soil water · Irrigation · O*ryza Sativa* · Productivity

Introduction

The concern with natural resources and the perception of the degradation of freshwater springs are important aspects of the environmental problem experienced by postmodern society. Population growth and the consequent increase in food demand have boosted production and consumption processes, intensifying the demand for natural resources (Hanjra & Qureshi, 2010; Rault et al., 2019). Therefore, the Earth system is headed for a collapse. Campbell et al. (2017) claim that agricultural production, due to its high demand, is one of the main causes that lead the Earth system to exceed planetary limits. This situation tends to worsen with the growth of the world population. According to the United Nations Department of Economic and Social Affairs (2022), by the middle of this century, the world population will reach about 9.7 billion people. In addition, we are facing global climate changes that lead to increased temperatures, high concentrations of carbon dioxide, changes in rainfall patterns, and extreme weather events (IPCC, 2018). Agricultural production is the most vulnerable area to climate change, and the potential decrease in productivity might lead to greater demand for water to maintain sustainable yields. (Bocchiola et al., 2013; Jiang et al., 2022; Yang et al., 2013). Considering

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climate changes, the degradation of the environment by anthropic actions, and the need of feeding the population, the quantification of water for the production of a good or service is essential for proposing measures to better manage natural resources, especially water resources. Among these measures, the water footprint stands out, since agricultural production is the practice that uses the most water on the planet, with emphasis on irrigated agriculture, which corresponds to more than 70% of global water use (Wu et al., 2022; Zhuo et al., 2019).

The water footprint of the rice crop (*Oryza sativa*) is approximately 1325 m^3 of water per ton of grain produced, considering the average of the 13 largest rice-producing countries between 2000 and 2004 (Chapagain & Hoekstra, 2011; Hoekstra & Mekonnen, 2012). Hoekstra and Hung (2002) demonstrate that, by quantifying the water incorporated into products, it is possible to understand the global character of freshwater and quantify the effects of consumption and trade on the use of water resources. Although there are several works that address the water footprint in rice production (Chapagain & Hoekstra et al. (2011), Xinchun et al. (2018), and Yang et al. (2018)), the quantification of this production is still little studied in Brazil. Rice is one of the most consumed foods in the world (FAO, 2018).

Brazil is the largest producer of this grain among American countries, and the state of Rio Grande do Sul is the largest national producer, with a share of about 70% of the production (IRGA, 2019). Thus, the importance of agricultural production of this grain for the Rio Grande do Sul and for supplying the national and even world markets is evident. This paper aims to define the water footprint of irrigated rice crop in the state of Rio Grande do Sul, in the 2019/2020 crop, to demonstrate the importance of quantifying water in cultivated areas for the conservation of water resources.

Materials and methods

Water footprint

The expression water footprint (WF) is used to measure the amount of fresh water used in the production of goods and services in a given activity, region, or country. This term was proposed in 2002 by the engineer Arjen Hoekstra and is an indicator of freshwater use that not only considers direct water use by a consumer or producer but also includes indirect water use (Mekonnen & Hoekstra, 2011). The expression was chosen in analogy to the ecological footprint (EF), but with a different focus, since EF is expressed in hectares and defined as the ecosystem area used to ensure the survival of a population or system (Wackernagel & Rees, 1996). WF indicates the amount of freshwater, usually measured in $m^3\ t^{-1}$, necessary for a population (Hoekstra & Chapagain, 2007; Silva et al., 2013). WF is important because it measures the amount of water involved in the entire production chain, considering the specific characteristics of each producing region and the environmental and technological characteristics that were used to generate that product. Thus, it is possible to follow the steps of the production process and evaluate in detail each element, the impacts, and the use of water resources involved in the process, from its basic raw material to energy consumption (Chapagain & Hoekstra, 2011). Aiming at a more detailed analysis, the methodology assumes that the water used to generate a product is classified into three segments: green, blue, and gray WF. Therefore, the WF is the sum of the calculation of the WF_{green}, WF_{blue}, and WF_{gray} (Eq. 1), expressed in $m^3\ t^{-1}$.

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

As shown in Fig. 1, WF Green addresses the plant's demand for rainwater, WF Blue addresses the demand for irrigation water by the plant plus percolation losses, while the WF Gray accounts for the degree of water contamination by fertilizers and pesticides used in the process (Hoekstra & Chapagain, 2007; Silva et al., 2013).

Green water footprint (WF_{green})

WF_{green} refers to the amount of water used during the production process, derived from precipitation and stored in the soil after infiltration, and concerns the use, mainly, in forestry and agricultural crops. Hoekstra et al. (2009) and Wichelns (2010) state that WF_{green} is a determining fraction in the calculation of the WF of agricultural products, because it demonstrates the total amount of evaporated water from the fields of cultivation at the time when the crop

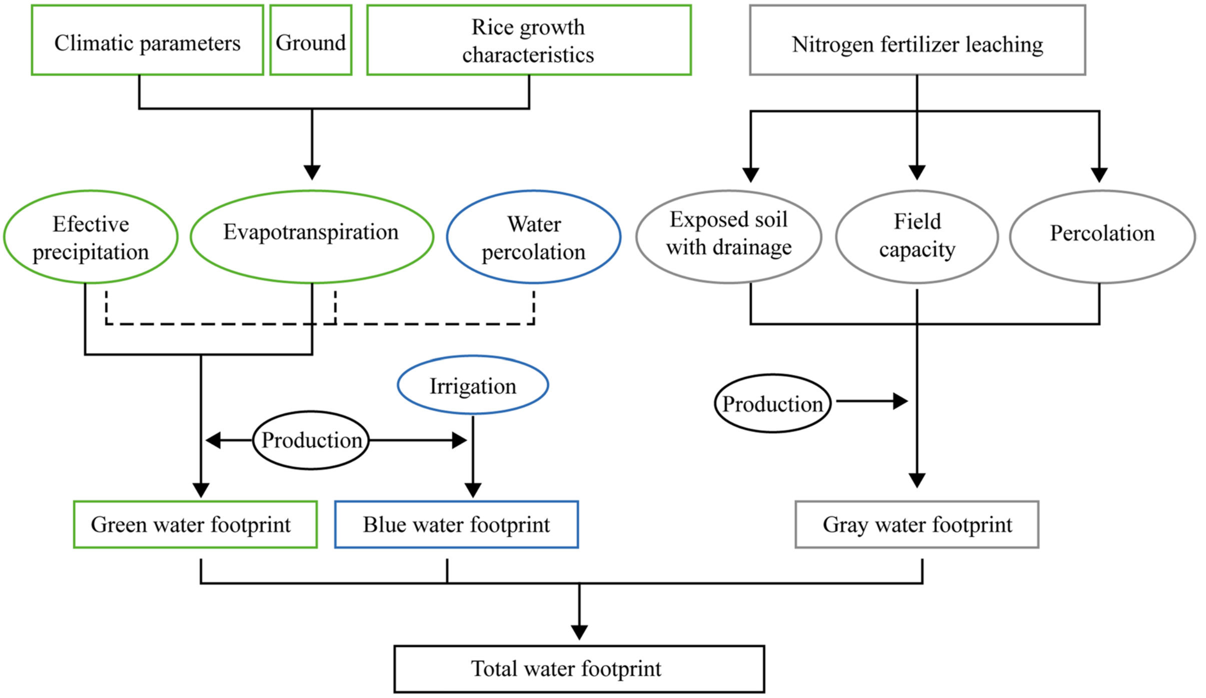

Fig. 1 Procedure for determining the water footprint source: Adapted from Li et al. (2018)

was growing. Each crop needs a favorable period during the year so that it can develop properly, and each soil has its own characteristics, which leads to the evaporation of water from the soil in different ways, depending on its characteristics, including transpiration by plants and other forms of evaporation (Bleninger & Kotsuka, 2015; Hoekstra et al., 2009; Wichelns, 2010; Xinchun et al., 2018).

The $\mathrm{WF}_{\mathrm{green}}$ calculation can be determined according to the following equations:

$$WF_{\mathrm{green}} = \frac{\mathrm{DHC}_{\mathrm{green}}}{P} \quad (2)$$

$$\mathrm{DHC}_{\mathrm{green}} = 10 \times \sum\nolimits_{\mathrm{d=1}}^{\mathrm{pdc}} \mathrm{ET}_{\mathrm{green}} \quad (3)$$

$$\mathrm{ET}_{\mathrm{green}} = \min\left(\mathrm{ET}_{\mathrm{c}}, P_{\mathrm{efet}}\right) \quad (4)$$

If $P_{\mathrm{efet}} \geq \mathrm{ET}_{\mathrm{c}}$, green water = ET_{c}; if $P_{\mathrm{efet}} < \mathrm{ET}_{\mathrm{c}}$, green water = P_{efet}. Considering the sum of ET_{c} and P_{efet} referring to the following periods of the crop cycle: 1–30, 31–60, 61–90, and 91–120 days.

$$\mathrm{ET}_{\mathrm{c}} = \mathrm{ET}_{\mathrm{o}} \times K_{\mathrm{c}} \quad (5)$$

$$\mathrm{ET}_{\mathrm{o}} = \mathrm{Penman-Monteith-FAO\ equation} \quad (6)$$

$$P_{\mathrm{efet}} = \left(\frac{P_{\mathrm{total}}}{125}\right) \times \left(125 - 0.2 \times \mathrm{P}_{\mathrm{total}}\right) \text{ If } P \text{ total} < 250 \text{ mm} \quad (7)$$

$$P_{\mathrm{efet}} = 125 + 0.1 \times P_{\mathrm{total}} \text{ If } P \text{ total} \geq 250 \text{ mm} \quad (8)$$

in which $\mathrm{WF}_{\mathrm{green}}$ = green water footprint ($\mathrm{m}^3\ \mathrm{t}^{-1}$); $\mathrm{DHC}_{\mathrm{green}}$ = water demand of the green crop ($\mathrm{m}^3\ \mathrm{ha}^{-1}$); P = grain yield ($\mathrm{t\ ha}^{-1}$); factor 10 converts "mm" into "$\mathrm{m}^3\ \mathrm{ha}^{-1}$"; $\mathrm{ET}_{\mathrm{green}}$ = evapotranspiration referring to green water (mm day_{-1}); ETc = crop evapotranspiration (mm day−1); ET_{o} = reference evapotranspiration (mm day^{-1}); K_{c} = crop coefficient; pdc = refers to the duration of the crop development period in days (emergence harvest); P_{efet} = effective precipitation (mm), considering the sum of values for periods of 30 days; and P_{total} = total precipitation (mm), considering the sum of values for periods of 30 days.

Effective precipitation refers to the volume of rainwater stored in the soil, the water that does not reach the deeper layers of the soil, does not evaporate, or is lost by surface runoff. This water remains available for use in agriculture and has great relevance in the agricultural sector (Dastane, 1974; USDA, 1993).

Blue water footprint (WF_{blue})

WF_{blue} refers to the amount of freshwater used in the production process, which is taken from surface and underground water bodies and does not return, being considered a consumptive use. During the process, this water may have been evaporated or incorporated in the formation of the product; it may also not return to the basin in the same period it drained or even not return to its original basin (Hoekstra et al., 2011). In agricultural cultivation, the evaporation of irrigation water in the planting regions is included (Hoekstra et al., 2009; Wichelns, 2010).

In the case of irrigated rice, the loss of water through percolation is an important factor for its low efficiency, threatening its sustainability (Kukal & Aggarwal, 2002). In addition, the percolation rate depends on factors such as soil type, its percentage of sand, silt and clay, particle density, organic matter, and moisture content (Plate et al., 2019); soil preparation (Almeida et al., 2018); and water depth height (Sudhir-Yadav et al., 2012). In agriculture, WF_{blue} includes evapotranspiration, effective precipitation, and percolated water (Hoekstra et al., 2009; Li & Ren, 2019; Wichelns, 2010). And it is expressed by the following equations:

$$WF_{blue} = \frac{DHC_{blue}}{P} \tag{9}$$

$$DHC_{blue} = 10 \times \left(\sum_{d=1}^{pdc} ET_{blue} + PL \right) \tag{10}$$

in which WF_{blue} = blue water footprint ($m^3\ t^{-1}$), DHC_{blue} = water demand of the blue crop ($m^3\ ha^{-1}$), ET_{blue} = evapotranspiration referring to blue water ($mm\ day^{-1}$), and PL = deep percolation ($mm\ day^{-1}$).

$$ET_{blue} = \max\ \left(0, ET_c - P_{efet}\right) \tag{11}$$

in which if $P_{efet} \geq ET_c$, blue water = 0; if $P_{efet} < ET_c$, blue water = $ET_c - P_{efet}$. Considering the sum of ET_c and P_{efet} referring to the following periods of the culture cycle: 1–30, 31–60, 61–90, and 91–120 days.

Gray water footprint (WF_{gray})

WF_{gray} refers to the water that has become polluted during the production process, being defined as the amount of water necessary to dilute the pollutant load to acceptable levels, established in the existing quality and potability standards. Although gray water does not necessarily represent water entering the system, it makes up the WF because it represents the volume of water necessary for the total neutralization of the environmental load sent to water bodies (Bleninger & Kotsuka, 2015; Hoekstra et al., 2009; Xinchun et al., 2018), expressed by Eq. (12):

$$WF_{gray} = \frac{(\alpha\ TQ)/\left(C_{max} - C_{nat}\right)}{P} \tag{12}$$

in which WF_{gray} = gray water footprint ($m^3\ t^{-1}$); α = fraction of leaching and runoff; TQ = chemical application rate ($kg\ ha^{-1}$); chemical application rate is the dose of nitrogen fertilizer applied during rice cultivation ($120\ kg\ ha^{-1}$ of N); Cmax = maximum admissible concentration of the pollutant in the aquatic environment ($kg\ m^{-3}$); and C_{nat} = natural concentration of the pollutant in the aquatic environment ($kg\ m^{-3}$), considering that nitrogen is the critical pollutant of the irrigated rice crop, the reference value for Cmax is $0.0133\ kg\ m^{-3}$, which corresponds to the value of total ammoniacal nitrogen for fresh waters of class 3, according to the resolution 357 of the National Council for the Environment (CONAMA, 2005); the C_{nat} value is $0\ kg\ m^{-3}$; P = grain yield ($t\ ha^{-1}$).

Study area

The state of Rio Grande do Sul cultivates about 1 million ha of irrigated rice, distributed in six regions: West Border (WB), Campanha (CA), Central Region (CR), Internal Coast Plain (ICP), External Coast Plain (ECP), and South Zone (SZ) (IRGA, 2019), shown in Fig. 2.

Weather data

Meteorological data for the simulated period (2019/2020 crop) were obtained from automatic monitoring stations installed in the municipalities of

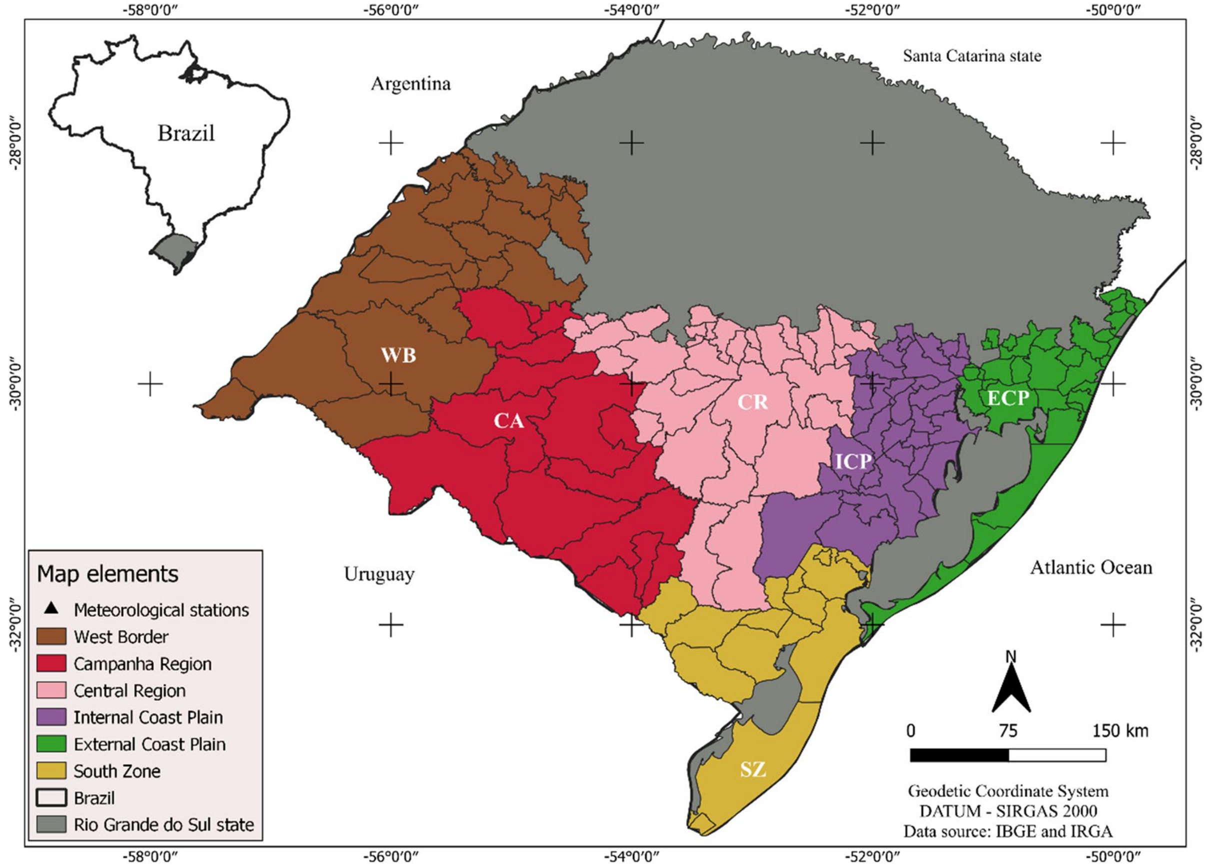

Fig. 2 Spatialisation of the six irrigated rice-producing regions in the state of Rio Grande do Sul

Uruguaiana, Dom Pedrito, Santa Maria, Camaquã, Porto Alegre, and Rio Grande, which represent the regions WB, CA, CR, ICP, ECP, and SZ, respectively. The choice of these municipalities is due to the presence of meteorological stations from National Institute of Meteorology (INMET). Daily data on solar radiation, minimum and maximum air temperature, relative air humidity, wind speed, precipitation, and crop evapotranspiration were retrieved from http://sisdagro.inmet.gov.br/.

Results and discussion

The 2019/2020 crop had the highest average irrigated rice productivity in the history of Rio Grande do Sul, 8402 kg ha^{-1} (IRGA, 2019). The WB region surpassed the 9000 kg ha^{-1} threshold. Figure 3 presents the average productivity of the rice-producing regions in the state, with emphasis on the WB and SZ regions, which crop values of 689 kg ha^{-1} and 386 kg ha^{-1} above the state average. The CA, ICP, CR, and ECP regions crop 38 kg ha^{-1}, 432 kg ha^{-1}, 704 kg ha^{-1}, and 1004 kg ha^{-1} less than the state average, respectively.

Weather data

The values observed at the meteorological stations are presented in Table 1, with cumulative values for evapotranspiration and precipitation variables. The maximum and minimum temperature and solar radiation variables are presented by means. The sampling period ranges from 11 November 2019 (emergence date) to 9 March 2020 (harvest date), totaling a 120-day interval.

As per the values in Table 1 for the growing season, which is from seedling emergence to the

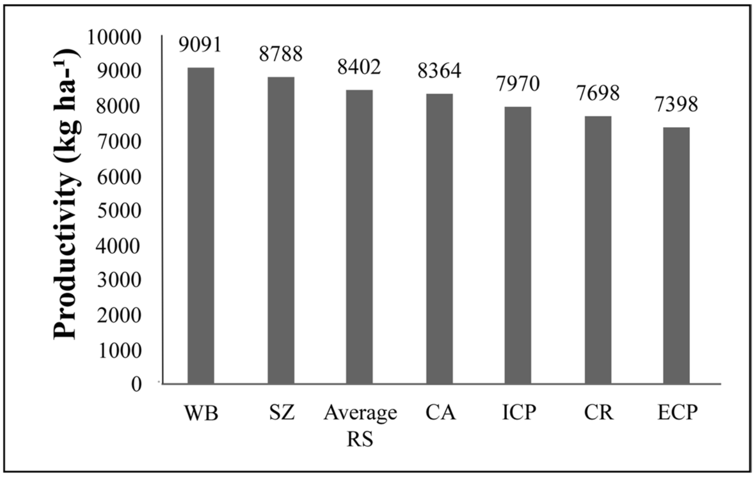

Fig. 3 Average productivity of the rice growing regions and the state of Rio Grande do Sul. Source: IRGA (2020)

Table 1 Weather data of the six rice growing regions of the state of Rio Grande do Sul during the period from 11 November 2019 (date of emergence) to 9 March 2020 (harvest date)

Rice growing region (municipality)	Period	Crop evapotranspiration (mm)	Total precipitation (mm)	Maximum temperature (°C)	Minimum temperature (°C)	Global solar radiation (MJ m^{-2})
West Border (Uruguaiana)	1–30 days	216	158	30.0	17.0	807
	31–60 days	223	83	32.1	18.6	838
	61–90 days	221	159	32.8	20.8	766
	91–120 days	204	104	31.1	17.6	731
Campanha Region (Dom Pedrito)	1–30 days	205	44	29.1	15.0	808
	31–60 days	262	23	32.1	17.5	770
	61–90 days	231	98	32.0	19.0	779
	91–120 days	215	36	30.7	15.8	731
Central Region (Santa Maria)	1–30 days	152	57	29.7	16.7	746
	31–60 days	178	77	32.5	18.8	774
	61–90 days	136	252	30.9	20.2	720
	91–120 days	134	52	30.4	16.9	702
Internal Coast Plain (Camaquã)	1–30 days	104	47	28.0	15.5	759
	31–60 days	121	79	31.3	18.2	762
	61–90 days	95	152	30.0	19.6	673
	91–120 days	89	35	29.6	16.9	640
External Coast Plain (Porto Alegre)	1–30 days	135	49	29.5	17.6	786
	31–60 days	179	16	33.1	20.5	788
	61–90 days	157	79	32.1	21.4	703
	91–120 days	139	83	30.9	19.4	692
South Zone (Rio Grande)	1–30 days	169	21	26.0	17.5	769
	31–60 days	180	53	28.5	20.0	740
	61–90 days	196	25	29.1	20.8	732
	91–120 days	177	25	28.5	18.5	663

Source: SISDAGRO: crop evapotranspiration, total precipitation, maximum temperature, minimum temperature. INMET: solar radiation

60th day, in relation to crop evapotranspiration and precipitation, all rice growing regions, there was greater evaporation than precipitation. Values of 400, 298, 249, 198, 196, and 99 mm more of evapotranspiration were observed, respectively, for the regions of CA, SZ, ECP, WB, CR, and ICP. In the reproductive period, which is from the 61st day until crop, values of 323, 312, 162, and 134 mm more evapotranspiration than precipitation were observed for the SZ, CA, WB, and ECP regions, respectively. In the CR and ICP regions, values of 34 and 3 mm, respectively, of precipitation more than evapotranspiration were observed. Evapotranspiration depends on climatic factors, such as relative humidity, amount of light, and wind speed, among others (Allen et al., 1998). At the beginning of the crop cycle, evapotranspiration is mostly composed of surface water evaporation, but as the crop grows and shades the water, evaporation decreases and transpiration increases (Santos et al., 2010). Regarding the temperature, all regions had some cold waves, mainly in the first 30 days, which are anomalous records for the summer, reaching temperatures of 15 °C in the CA region. Maximum temperatures, with the exception of the WB and SZ regions, were recorded in the vegetative phase, however, in the second month of plant development.

As for solar radiation, it appears that the highest incidences, for all regions, occurred in the vegetative phase, with the highest values for the WB, CA, ECP, ICP, CR, and SZ region, respectively. In the reproductive phase, the highest radiations were observed in the WB, CA, CR, SZ, ECP, and ICP regions. In addition, as expected, higher incidences of solar radiation led to greater evapotranspiration, as Table 2 shows. This phenomenon also occurs in relation to temperature versus solar radiation, according to the Penman-Monteith-FAO radiation equation (Allen et al., 1998).

For the values of meteorological variables versus productivity and WF (Table 2), there is a very strong positive correlation between radiation and evapotranspiration and between evapotranspiration and WF, highlighting the importance of measuring evapotranspiration for determining WF, especially WF_{green} and WF_{blue}. In relation to evapotranspiration, there is a moderate positive correlation with productivity. Regarding temperature and radiation, the Instituto Rio Grandense do Arroz (IRGA, 2019) states that for the irrigated rice crop to reach high yields, temperatures between 24 and 30 °C and high incidence of direct sunlight are needed. However, very high temperatures, above 30 °C, can harm the plant, especially during the flowering period, as shown in Table 2.

Determination of WF

The WF determination was divided between the vegetative and reproductive periods of the plant, segmented into WF_{green}, WF_{blue}, and WF_{gray} (Fig. 4), in the six rice growing regions of the state of Rio Grande do Sul. Regarding the vegetative phase, the highest WF_{green} occurred in the WB, CR, ICP, ECP, SZ, and CA regions, respectively. However, in this phase, WF_{blue} had higher values for all regions, which can be explained by the need for a water depth over the crop, increasing evapotranspiration and percolation values. In addition, WF_{blue} derives from the volume of underground or surface water consumed during cultivation, that is, it is the water inserted, irrigated, in the cultivation system. For all regions the WF_{gray} values were low.

In the reproductive phase, an increase in WF_{green} and a decrease in WF_{blue} were observed for all regions, except for SZ. For WF_{gray}, the values were similar in the two analyzed periods in all regions. Briefly, for the period under analysis, an average

Table 2 Correlation analysis

	Evp	Precip	Max. temp	Min. temp	Radiation	P	WF
Evp	1.00	−0.02	0.25	−0.16	0.91	0.63	0.93
Precip	−0.02	1.00	0.58	−0.14	0.27	0.10	−0.09
Max. temp.	0.25	0.58	1.00	−0.11	0.58	−0.28	0.43
Min. temp.	−0.16	−0.14	−0.11	1.00	−0.02	−0.15	−0.11
Radiation	0.91	0.27	0.58	−0.02	1.00	0.43	0.91
P	0.63	0.10	−0.28	−0.15	0.43	1.00	0.30
WF	0.93	−0.09	0.43	−0.11	0.91	0.30	1.00

Evp crop evapotranspiration, *precip* precipitation, *max. temp.* maximum temperature, *min. temp.* minimum temperature, *P* productivity.

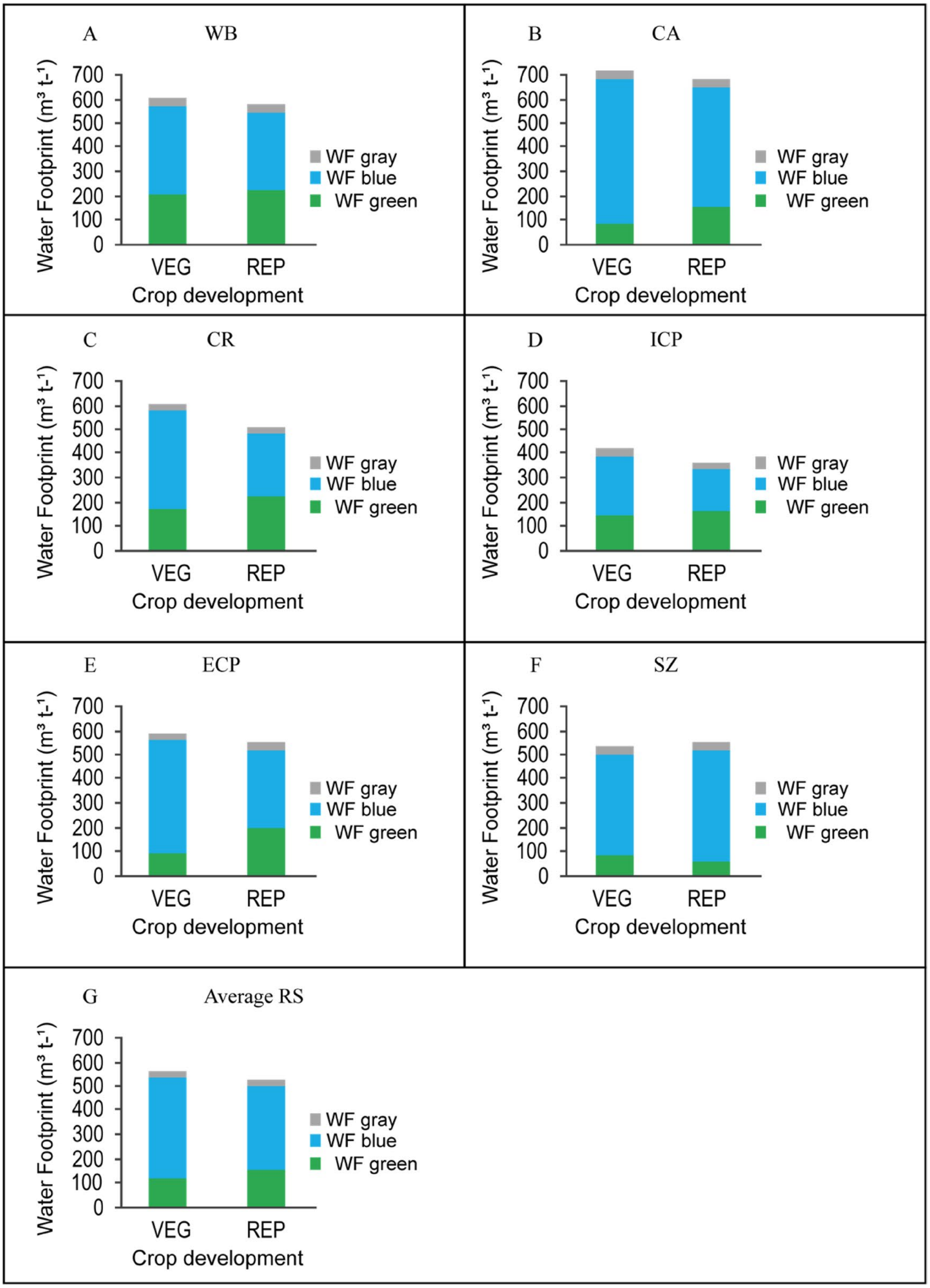

Fig. 4 Water footprint in the six rice growing regions of the state of Rio Grande do Sul

value of 1093.22 m^3 t^{-1} was verified for the state of Rio Grande do Sul. From this total, 27, 68, and 5%, respectively, correspond to WF_{green}, WF_{blue}, and WF_{gray}.

Table 3 compares the results obtained in this research with values presented in the literature. For most of the presented authors, WF_{green} is greater than WF_{blue}, which does not coincide with our findings. Also, for WF_{gray}, the values presented in the literature are well above the values presented in this paper.

The estimation of crop water consumption is mainly based on models such as Penman-Monteith (Eq. 6) and Shuttleworth-Wallance (Chen et al., 2021), which calculate crop evapotranspiration considering the crop coefficient to obtain total accumulated water consumption during the growing period. Nevertheless, Jiang et al. (2022) report that these methods ignore the relationship between some environmental factors (such as soil texture types and field management measures) and water supply and demand for crops, as well as assuming that crops always grow under ideal conditions. Thus, to correctly quantify the volume of water needed to calculate the water footprint of a crop, it is essential to use specific parameters of the crop and the location where it is located (Bocchiola et al., 2013; Chapagain & Hoekstra, 2011; Mekonnen & Hoekstra, 2020; Nana et al., 2014).

Strategies for reducing the water footprint

WF is determined by the relationship between crop productivity and the corresponding water consumption during the growth period. Consequently, if there is an increase in productivity, there will be a decrease in WF. In this context, governmental and private agricultural research agencies are important for the insertion of cultivars that have high productive potential and a shorter cycle. Chapman et al. (2012) comment that suitable varieties can mitigate the effects of climate change, including its impacts on the efficiency of water use and agricultural production.

During approximately 80% of their growing season, irrigated floodplain rice ecosystems in Southern Brazil are maintained at a water depth of 5 to 10 cm (Timm et al., 2014). This layer forms an immense water surface causing a high volume of evapotranspiration (Table 1). According to our findings, an

Table 3 Water footprint of the six IRGA rice paddies and values found in the literature

IRGA regions	WF_{green} (m^3 t^{-1})	WF_{blue} (m^3 t^{-1})	WF_{gray} (m^3 t^{-1})	WF (m^3 t^{-1})
WB	435.07	702.87	49.62	1187.57
CA	214.61	1079.38	53.94	1347.93
CR	393.01	606.72	58.60	1058.33
ICP	302.78	423.68	56.60	783.06
ECP	272.41	782.59	60.98	1115.99
SZ	132.74	882.39	51.33	1066.47
Values presented by authors from countries other than Brazil				
Bulsink et al. (2010) Indonesia	2528	733	212	3473
Chapagain and Hoekstra (2011) China	367	487	117	971
Mekonnen and Hoekstra (2011) Global	1146	341	187	1673
Xinchun et al. (2018) East China	586	454	720	1760
Zhuo et al. (2016) China	414	225	5164	5803
Yang et al. (2018) South China	476	310	278	1064
Yoo et al. (2014) South Korea	295	502	48	845

Source: By the author (adapted from Xinchun et al., 2018) average of 6863 m^3 ha^{-1} of water evaporated during the plant cycle, values that are in accordance with Böcking et al. (2008) and Massey et al. (2014). In this sense, proper irrigation management is essential for increasing the ratio of water consumption versus productivity (Cao et al., 2021). In experiments carried out in Uruguay, Carracelas et al. (2019) concluded that techniques which kept water in the soil under saturated conditions with intermittent flooding allowed for the reduction of water input without significant effects on grain yield.

Understanding the type of source and the amount of water for rice production is very important for improving production and management of water resources (Mekonnen & Hoekstra, 2020). The state of Rio Grande do Sul cultivates about 1 million ha (SOSBAI, 2018), of which about 47% is irrigated from built reservoirs, 32% from streams and rivers, 20% from ponds, and 0.1% from other sources (IRGA, 2006). Therefore, understanding and updating the water sources to supply the rice crop are essential for better management of water resources in the basins where production takes place. Albers et al. (2021) raise the issue of water use, in a regional context, in which the demands must be observed at the watershed level according to the use needs of the different actors.

Regarding WF_{gray}, Wu et al. (2022) analyzed different forms of management in China, through experiments with common flooding and intermittent flooding. The authors concluded that the loss of pollutants (total nitrogen (NT) and total phosphorus (TP)) occurs in two ways, by percolation and by surface drainage. There is a greater loss of NT, around 7%, in the continuous flooding system, which saves the proper irrigation management in the crop, because, in addition to reducing irrigation costs, the possible outputs of this water into water bodies, with high concentrations of N and P, may lead to the process of eutrophication.

Conclusions

This research aimed to define the WF of the irrigated rice crop in the state of Rio Grande do Sul, in the 2019/2020 crop, in order to demonstrate the importance of quantifying water for this crop, due to the high water volume required for its growth production. The study estimated the WF values in the six rice growing regions of the state of Rio Grande do Sul, categorizing the analyzes into the vegetative and reproductive phases of the plant. In both phases, WF_{blue} had higher volumes, which shows the dependence of irrigation on the crop. Thereby, the application of good cultivation practices provides the best management for water conservation within the crop and, consequently, reduces its cost, increases its production, and decreases WF_{gray} values. Among these management practices, control of the amount of water needed to dilute the agricultural pollutant and drainage for irrigated rice cultivation stands out. These are factors that interfere with the volume of water and nutrients that the plant needs, together with the control between the land preparation and the opportune sowing period. In addition, such factors contribute to reducing losses and having a good result in productivity and, consequently, in the reduction of the water footprint.

Evaluating from an environmental point of view, it is known that the production of irrigated rice is linked to the large volume of water used for its cultivation. This fact, in many cases, can lead to disputes over the right to use water, mainly in cases of scarcity of water resources. In this perspective, the determination of the amount of water consumed through WF is a highly important tool both quantitatively and qualitatively.

Author contribution All authors contributed to the study's. Specifically,

Fabiane Recktenwalt - Development of the methodology; creation of the manuscript, specifically writing the initial draft.

Francisco Alexandre de Moraes - Responsible for critical review; commentary and revision.

Marco Alésio Figueiredo Pereira - Responsible for conceptualization ideas; formulation and evolution of the overarching research and aims; Oversight and leadership responsibility for the research activity planning and execution; substantive translation, commentary and revision.

Funding The first and second authors thank the CAPES for providing scholarships during the postgraduate period, period of this study. The third and fourth authors thank the Fapergs – Gaúcho Researcher Public Notice 05/2019.

Data availability All data and materials are available from the corresponding author on specific request.

Declarations

Competing interests The authors declare no competing interests.

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