ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

PEGADA HÍDRICA DO ARROZ CULTIVADO SOB DIFERENTES MANEJOS DE IRRIGAÇÃO

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1 RESUMO

O arroz é um dos cereais mais produzidos e consumidos no mundo. O manejo da água na orizicultura é complexo, sendo os estudos acerca da pegada hídrica do arroz menos frequentes em relação a outras culturas. O objetivo deste trabalho foi estimar de forma simplificada a pegada hídrica do arroz irrigado por aspersão e inundação sob diferentes manejos de irrigação, adotando como base a metodologia tradicional de estimativa da pegada hídrica. Os dados utilizados são provenientes de dois experimentos conduzidos na Estação Experimental Terras Baixas, Empresa Brasileira de Pesquisa Agropecuária (Embrapa) Clima Temperado, Capão do Leão, RS, Brasil. No Experimento 1 foram analisados três manejos de irrigação na safra do arroz de 2011/2012 e quatro na safra de 2012/2013. No Experimento 2 foram analisados quatro manejos de irrigação nas safras 2015/2016 e 2016/2017. Os manejos nas tensões de 20 e 10 kPa (aspersão) e por irrigação contínua (inundação) apresentaram menor pegada hídrica simplificada. Comparando-se a irrigação por aspersão e inundação, concluiu-se que na inundação, o manejo de irrigação contínua resultou em uma pegada hídrica simplificada menor.

Palavras-chave: *Oryza sativa*, métodos de irrigação, inundação, aspersão

MANKE, E. B.; SANTOS, A. F. dos; PINTO, M. A. B.; PARFITT, J. M. B.; BAMBERG, A. L.; FARIA, L. C.
WATER FOOTPRINT OF RICE CULTIVATED UNDER DIFFERENT IRRIGATION MANAGEMENTS

2 ABSTRACT

Rice is one of the most produced and consumed cereals in the world. The water management in rice farming is complex, and studies on the rice water footprint are less frequent than other cultures. The objective was to estimate the simplified water footprint of a sprinkler and flood-irrigated rice under different irrigation management, taking as model the traditional methodology of water footprint estimation. The raw data used are from two experiments

Recebido em 13/11/2020 e aprovado para publicação em 22/01/2021
DOI: http://dx.doi.org/10.15809/irriga.2021v1n2p248-263

performed using rice in the “Terras Baixas”, Experimental Station, Brazilian Agricultural Research Corporation (Embrapa) Temperate Climate, located in Capão do Leão, RS, Brazil. In Experiment 1, three irrigation management applied in the rice cropping season of 2011/2012 and four in the cropping season of 2012/2013 were analyzed. In Experiment 2, four irrigation managements in the 2015/2016 and 2016/2017 cropping seasons were evaluated. The irrigation managements in the tensions of 20 and 10 kPa (sprinkler) and continuous irrigation (flood) presented smallest simplified water footprint. Comparing sprinkler and flood irrigation, it can be concluded that the flood method, under continuous irrigation, resulted in a smallest simplified water footprint.

Keywords: *Oryza sativa,* irrigation methods, flooded, sprinkler

3 INTRODUCTION

Rice is the second most produced cereal in the world. It is estimated that the global production in 2018 was 750 million tons of hulled grains (FOOD AND AGRICULTURAL ORGANISATION, 2020) and that approximately half of the world's population uses it as their main source of calories (MUTHAYYA et al., 2014). According to the Department of Economics and Statistics, in Rio Grande do Sul (RS), rice is predominantly grown in lowlands and is directed to supply the Brazilian market, whose demand has remained stable in the last decade (FEIX; LEÚSIN JÚNIOR, 2019). In the 2018/2019 harvest, the RS produced 7,241,458 million tons, with an average productivity of 7,508 kg ha $^{-1}$ (INSTITUTO RIO GRANDENSE DE ARROZ, 2019).

Rice production uses irrigation methods and management to ensure high productivity (CONAB, 2016). Rice cultivation differs from that of most crops in that, as a semiaquatic annual grass, the presence of a water table throughout most of the growing cycle is crucial for achieving high productivity. Water harvesting from water sources for crop supplementation is essential (HONGYING et al., 2017). Therefore, the management and rational use of water in rice cultivation represents a significant challenge compared with other crops.

Population growth and food consumption have increased the frequency of conflicts over water availability and quality worldwide. This has led the public and private sectors to recognize water use and water footprint estimation as important issues for water security (LAMASTRA et al., 2014). Therefore, aiming for the rational use of water resources, some researchers have used existing methodologies and adapted the methodology for calculating the water footprint of rice, as observed in the studies by Sheresta, Chapagain, and Babel (2017), Hongying et al. (2017), Xinchun et al. (2018), and Arunrat et al. (2020).

According to Silva et al. (2013), the water footprint can be considered a methodology that makes it possible to measure the amount of virtual water used in a given product. Furthermore, according to Hoeskstra et al. (2011), defining the objective of calculating the water footprint is the first step in applying this concept.

The water footprint can be used to estimate the water used in a production process or in the cultivation of a specific crop (BLENINGER; KOTSUKA, 2015) and can also be used to assess the environmental, social and economic sustainability of a given product, aiming to minimize the total water used and enable efficient and, consequently, more sustainable production (HOEKSTRA et al., 2011).

The calculation of the total water footprint considers three types: the blue water footprint ($_{blue\ pH}$), the green water footprint ($_{green\ pH}$), and the gray water footprint ($_{gray\ pH}$) (EMPINOTTI; TADEU and MARTINS, 2013; ALMEIDA et al., 2019). The $_{blue}$ pH measures the amount of available water extracted from water sources over a given period; that is, it represents the volume of water that does not immediately return to the same watershed. The $_{green}$ pH is the volume of rainwater used during the production process, corresponding to the volume of rainwater stored in the soil and subjected to evapotranspiration in crop fields. According to Hoeskstra et al. (2011), the $_{gray}$ pH indicates the amount of water used to dilute pollutants on the basis of natural environmental patterns.

Accurately estimating the water footprint involves a series of factors and requires a significant amount of information, which is often not monitored at the rural property level. It has been the subject of several studies, some of which in Brazil relate to agricultural crops such as sugarcane (SILVA et al., 2015), cocoa (ORTIZ-RODRIGUEZ et al., 2015), cellulose (EMPINOTTI; TADEU; MARTINS, 2013), and soybean (BLENINGER et al., 2015), among others. However, research addressing this topic in its application to rice cultivation is rare.

In rice cultivation, the use of alternative irrigation methods can significantly reduce the volume of water extracted from water sources (blue water) and, correspondingly, improve water availability from rainfall events (green water). Furthermore, sprinkler irrigation and intermittent flood irrigation methods have gained attention for reducing the volume of water applied via irrigation during the crop cycle. However, it is crucial to also evaluate the impact of these alternative irrigation methods and management methods on crop productivity and verify whether they effectively reduce crop water footprints.

Thus, the objective of this work was to estimate the water footprint of rice crops irrigated by sprinklers and flooding under different irrigation practices in a simplified way, adopting the traditional methodology for estimating the water footprint as a basis.

4 MATERIALS AND METHODS

The data used come from experiments carried out with rice crops in an area located at the Terras Baixas Experimental Station (ETB) of the Brazilian Agricultural Research Corporation (Embrapa) temperate climate, Capão do Leão, in Rio Grande do Sul, Brazil. The soil is classified as a Haplic planessol (CUNHA; COSTA, 2013) and is present in large lowland territories of the RS.

The information provided corresponds to the field experiments carried out by Pinto (2015) and Parfitt et al. (2018), which used different irrigation methods and managements. For differentiation purposes, this work considers the classification of Experiment 1 to refer to the data of Pinto (2015) and that of Experiment 2 to refer to the data of Parfitt et al. (2018). The irrigation practices of Experiment 1 and Experiment 2 were carried out as shown in Table 1.

Table 1. Irrigation management was adopted on the basis of the crop development stage and soil water tension.

Experiment 1 - Sprinkler irrigation			
Irrigation Management		Irrigation	
Water Tension	Period	2011/2012 Harvest	2012/2013 Harvest
10 kPa	Final Paper		+
20 kPa	Final Paper	+	+
40/10 kPa	40 kPa - FV 10 kPa - FR		+
40/20 kPa	40 kPa - FV 20 kPa - FR	+	
40 kPa	Final Paper	+	+
Experiment 2 - Flood irrigation			
Water Tension	Period	2015/2016 Harvest	2016/2017 Harvest
IC	TPI	+	+
ICFI	RL	+	+
II 10 kPa	FAN	+	
II 40 kPa	FAN	+	
ICFI 40 kPa	FV		
II 40/10 kPa	40 kPa - FV 10 kPa - FR		+
II 40 kPa/ICFI	40 kPa - FV II - FA		+

Source: Adapted from Pinto (2015) and Parfitt et al. (2018)
TCC - entire crop cycle; FV - vegetative phase, i.e., from emergence to panicle differentiation (R1); FR - reproductive phase, i.e., from R1 onward; FA - aerated phase; IC - continuous flooding; ICFI - continuous flooding with intermittent water supply; II - intermittent irrigation; TPI - entire irrigation period: from water entry into the crop until physiological maturity of the crop; RL - water blade replacement to the maximum level.

Experiment 1 was carried out during the 2011/2012 and 2012/2013 rice harvests. The experimental area was irrigated with a mechanized mobile lateral sprinkler irrigation system (Valley®). The equipment is 275 m long and is divided into six spans, the last of which is cantilevered. The sprinklers installed in the mobile lateral irrigation system are the Senninger® I-Wob model, with a nozzle size of 16 (6.35 mm), and a 9-jet oscillating plate, with a maximum flow rate of 1,313 L h^{-1}.

In Experiment 1, the 2011/2012 harvest, three strips measuring 20 m wide and 40 m long were delimited, and irrigation management was based on soil water tension (Table 1). In the second harvest of Experiment 1 (2012/2013), the strips were 7 m wide and 40 m long. Soil water tension was monitored via Watermark® sensors installed at a depth of 0.10 m. At the first harvest, 12 sensors were used per strip, and at the second harvest, 14 sensors were used.

Experiment 2 was conducted during the 2015/2016 and 2016/2017 harvest seasons. The experimental area consisted of a 0.7 ha module that was irrigated by flooding. The area, with no difference in terrain level, was divided into four sections and subjected to different irrigation management systems.

In the 2015/2016 harvest, one of the management methods adopted was continuous flooding (IC), in which the water remains at the maximum level of the frame throughout the irrigation period (stage V4 to R7), with a water depth of 75 mm from V4 to R0 and a height of 100 mm from R0 to R7. The second method was continuous flooding with intermittent supply (ICFI), in which, after the first irrigation, with a 75 mm depth (V4), the management consists of interrupting the water supply to the crop until it reaches a level close to or equal to that of the soil so that the soil remains saturated throughout the rice cycle.

In Experiment 2, during the 2015/2016 harvest, rice management was also evaluated via two physical models involving intermittent flooding with return irrigation (II). Water depth maintenance was based on soil water tension, with water supplied during the aerated phase of the crop when tension reached 10 kPa in one model and 40 kPa in the other. The soil tension was monitored with Watermark® sensors. Monitoring was performed in six replicates per plot, and the sensor readings taken in the early morning were used to determine whether irrigation was necessary.

In the 2016/2017 harvest (Experiment 2), IC management was used in one of the physical models, and the ICFI was used in the other. Two II management practices were also used considering the soil water tension. One of these rice crop plots was irrigated with ICFI in the vegetative phase when the tension reached 40 kPa, and in the reproductive phase, regardless of the tension, ICFI was applied. In addition, ICFI was used when the tension reached 40 kPa in the vegetative phase and 10 kPa in the reproductive phase. The rice crop development cycle was monitored via the reference scale proposed by Counce, Keisling, and Mitchell (2000), and the date of the R0 phenological phase was determined via the degree-day method following the recommendations of STEINMETZ et al. (2004).

Table 2 shows the values of the water depths applied by the irrigation systems, as well as the precipitation and productivity of the rice crop during each of the harvests in Experiment 1 (PINTO, 2015) and Experiment 2 (PARFITT et al., 2018).

Table 2. Applied water depth, precipitation, effective rainfall (EC) and rice crop productivity in two agricultural harvests for each of the irrigation methods and management practices adopted.

Experiment 1 - Sprinkler irrigation				
Harvests	Management	Applied Water Surface (m³ ha^{-1})	Precipitation (mm)	Prod. (t ha^{-1})
2011/2012	20 kPa	2910	409	5.85
	40/20 kPa	2730		5.48
	40 kPa	2310		4.27
2012/2013	10 kPa	5340	429	7.38
	20 kPa	3150		4.5
	40 kPa	1860		3.37
	40/10 kPa	3990		6.36
Experiment 2 - Flood irrigation				
Harvests	Management	Applied Water Surface (m³ ha^{-1})	CE (mm)	Prod. (t ha^{-1})
2015/2016	IC	5140	77	10,459
	ICFI	5140	327	9,851
	II 10 kPa	5140	291	9,407
	II 40 kPa	5140	306	9,014
2016/2017	IC	4730	121	11.28
	ICFI	4730	187	10.80
	II 40 kPa/ICFI	4730	313	10.58
	II 40/10 kPa	4730	331	9.83

Source: Adapted from Pinto (2015) and Parfitt et al. (2018)
IC = continuous flooding; ICFI = continuous flooding with intermittent spraying; II 10 kPa = intermittent flooding with return irrigation with a soil water tension of 10 kPa in the aerated phase; II 40 kPa = intermittent flooding with return irrigation with tension of 40 kPa in the aerated phase; II 40/ICFI = intermittent flooding with return irrigation with tension of 40 kPa in the vegetative phase; II 40/10 kPa = intermittent flooding with return irrigation with tension of 40 kPa in the vegetative phase and 10 kPa in the reproductive phase; CE = effective rainfall; Prod. = Productivity.

The precipitation totals for Experiment 1, for both harvests, were provided by Embrapa Clima Temperado. Data for Experiment 2 were obtained via equipment installed in the rice field. In this experiment, a water meter was installed at the water inlet of each area module to quantify the volume used in each irrigation management. The daily rainfall in each area was obtained by recording the water depth in each experimental plot. Additionally, a rain gauge was installed to measure 24-hour rainfall, with measurements of water depth and accumulated precipitation in the rain gauge being taken simultaneously.

The amount of water used for the growth and development of rice is normally estimated through the water footprint, which considers the portion of water effectively incorporated by the plant through the crop's reference evapotranspiration, as proposed by Hoekstra et al. (2011).

In the flood irrigation method, even if only a portion of the water is actually used by the rice crop, the presence of a layer of water over the soil from the vegetative stage to physiological maturity generally favors its productivity. In other words, a crop responds positively when a certain volume of water is always available in its growing area, even if some of this water is not effectively involved in evapotranspiration. Thus, a layer of water remains constantly over the soil, meaning that the water collected from the source is specifically allocated for this purpose and limited to other possible uses.

On the basis of the findings of this study, a simplified methodology was adopted to estimate the WF of rice on the basis of the concepts defined by Hoekstra et al. (2011). The equations were adapted to estimate a value that represents the amount of water required by the rice crop throughout its cycle, that is, considering the water depth available to the plant and restricted to this use.

Equation (1) corresponds to the simplified blue water footprint ($_{blue}$ $_{pH}$), which relates the water depth available during the irrigation period of the rice crop to its productivity and is a simplification of the method proposed by Hoekstra et al. (2011).

$$PH_{azul} = \frac{10.LI}{P_{rtv}} \quad (1)$$

$_{blue}$ pH = Blue water footprint (m^3t^{-1})

LI = Irrigation blade multiplied by a factor of 10, which makes it possible to convert the water blade height in millimeters to the water volume per area (m^3 ha^{-1}).

P_{rtv} = Productivity (t ha^{-1})

The green water footprint ($_{green}$ $_{pH}$), presented in Equation 2, is obtained through the precipitation depth available in the soil after a rain event, which is used by the crop and contributes to maintaining the water height on the soil surface during cultivation for rice productivity.

$$PH_{verde} = \frac{10.P}{P_{rtv}} \quad (2)$$

$_{Green}$ pH = Green water footprint (m^3t^1)

P = Precipitation multiplied by a factor of 10, which allows the water depth to be converted in millimeters to the water volume per area (m^3 ha^{-1}).

P_{rtv} = Productivity (t ha^{-1})

In Experiment 1, the precipitation value was used, and in Experiment 2, the effective rainfall was considered to calculate the $_{green\ pH,}$ as shown in Table 2.

Equation (3) represents the estimate of the simplified water footprint (SWF), resulting from the sum of the simplified blue water footprint and the green water footprint, on the basis of the methodology of Hoekstra et al. (2011). However, a simplified water footprint was used because the gray water footprint, which is one of the components of the total water footprint, was not estimated.

$$PHS = PH_{azul} + PH_{verde} \quad (3)$$

PHS = simplified water footprint (m^3 t^{-1})

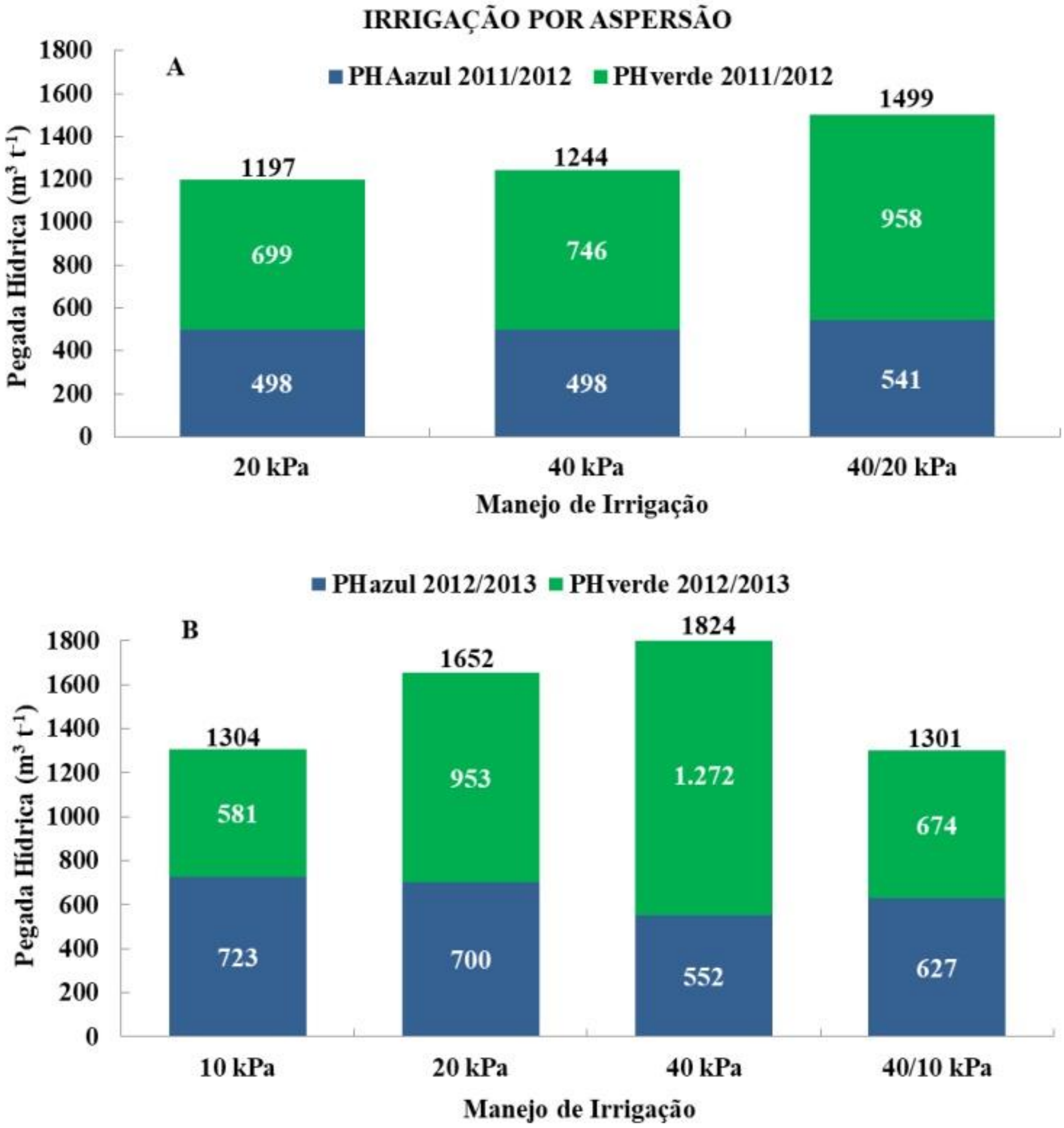
$_{blue}$ pH = Blue water footprint (m^3t^{-1})

$_{Green}$ pH = Green water footprint (m^3t^{-1})

5 RESULTS AND DISCUSSION

Figure 1 shows the results of the simplified blue water footprint and green water footprint estimates for Experiment 1, in which rice was irrigated by sprinkling with mobile lateral equipment under different irrigation management conditions during two harvests.

Figure 1. The simplified blue water footprint, green water footprint and simplified water footprint of Experiment 1, which were conducted under sprinkler irrigation and different irrigation depth management practices.



Source: Adapted from Pinto (2015)

In the 2011/2012 harvest, all the irrigation management systems evaluated presented a $_{green\ pH}$ higher than the simplified $_{blue\ pH}$ (Figure 1); that is, the amount of water made available by rain throughout the cultivation was greater than the volume captured from the water source.

A higher $_{green\ pH}$ represents a greater volume of precipitation available to plants and, consequently, a reduction in the amount of water obtained through supply sources, indicating the use of a shallower irrigation depth to meet the crop's water needs. According to Silva et al. (2015), blue water footprint values increase as irrigation increases. This statement is consistent with the simplified blue water footprint concept presented in this work, since this component represents the irrigation water used in the crop development process.

The results of the simplified $_{blue\ pH\ estimation}$ demonstrated that the values for irrigation management were the same as the average soil water tension limits of 20 and 40 kPa in the 2011/2012 harvests, which corresponded to 498 $m^3\ t^{-1,}$ as shown in Figure 1. Furthermore, irrigation management at tensions of 40/20 kPa according to the rice crop phase resulted in a relatively high simplified $_{blue\ pH}$ of 541 $m^3\ t^{-1}$, even though the $_{green\ pH}$ was 958 $m^3\ t^{-1}$, which was higher than that of the other phases.

A comparison of the three irrigation management systems also revealed that the method based on an average soil water tension of 20 kPa resulted in a lower PHS, resulting in 1197 $m^3\ t^{-1}$. In the sprinkler irrigation system (Experiment 1), the wetter the soil was (20 kPa and 40 kPa *versus* 40/20 kPa), the better the crop yield was. Thus, the sprinkler irrigation system at 20 kPa resulted in a lower PHS, resulting in greater water yield than those of the other management systems.

In the 2012/2013 harvest, as shown in Figure 1, the $_{green\ pH}$ was greater than the simplified $_{blue\ pH}$ in the 20 kPa, 40 kPa and 40/10 kPa management systems; that is, these systems presented a greater volume of water made available by rain in relation to that used through irrigation.

The irrigation management, which was based on an average soil water tension of 10 kPa, resulted in a relatively high simplified $_{blue}$ pH, which was associated with relatively high productivity (7.38 t ha^{-1}) among the management practices adopted with the sprinkler irrigation method (Table 2) and was also due to the relatively low contribution of the $_{green\ pH}$. On the other hand, the lowest simplified $_{blue\ pH}$ was obtained in the 40 kPa management system, which was related to the lower productivity (3.37 t $ha^{-1), also\ resulting\ in\ a\ higher}$ $_{green}$ pH value.

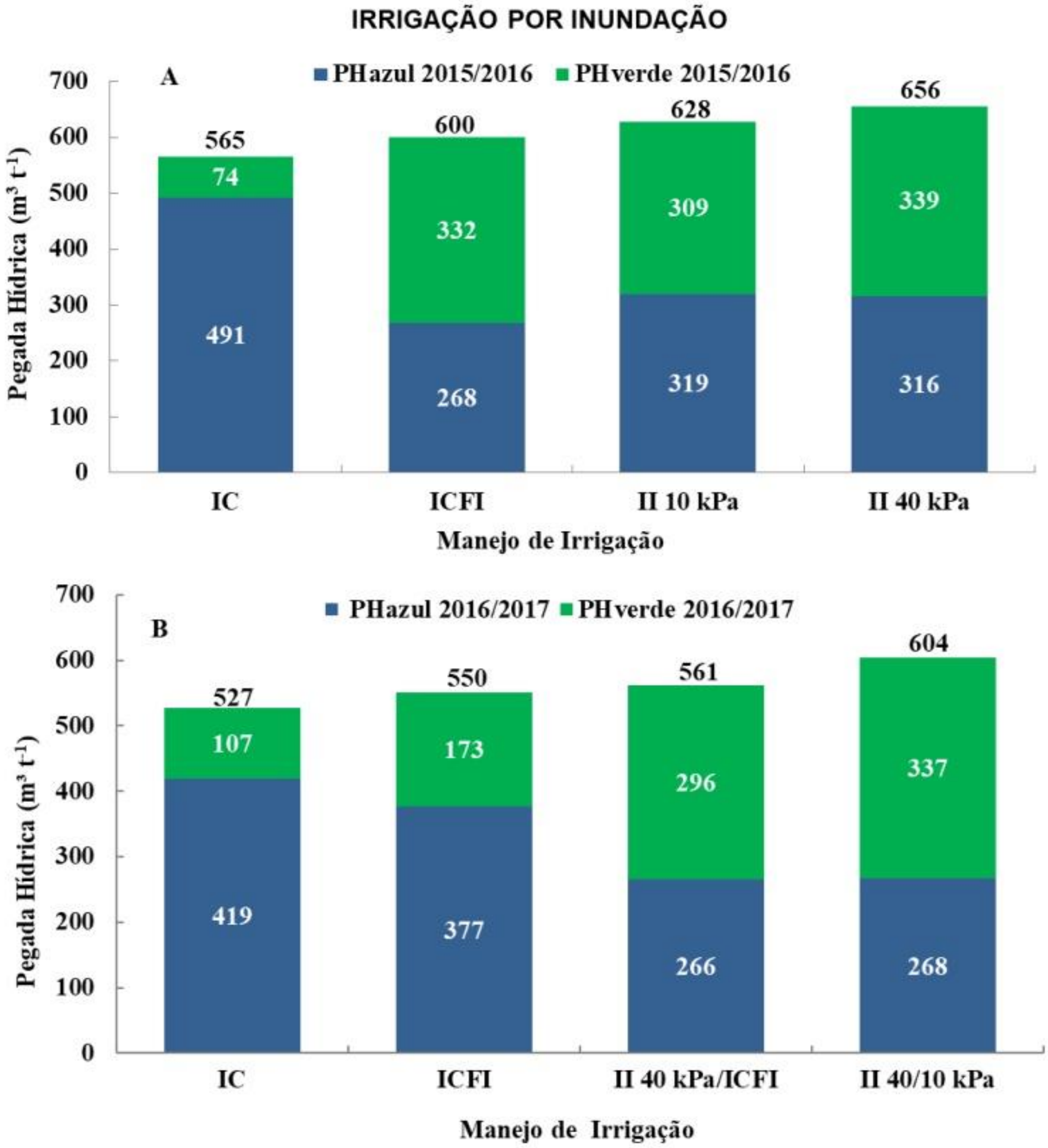
A comparison of the four irrigation management systems in the 2012/2013 harvest revealed that management criteria based on soil water tensions of 10 kPa and 40/10 kPa yielded the lowest simplified water footprints. Because these management systems yielded the highest yields, they also resulted in lower $_{green\ pH}$ and HSP values.

Low soil water tension provides water availability close to saturation, which favors rice crop development. According to Villa et al. (2006), maintaining a sufficient water depth in a flooded system provides beneficial effects on weed control, as it acts as a physical barrier, preventing weed seed germination by reducing oxygenation of the soil surface. This condition is possible in sprinkler systems when the lowest irrigation management tensions are adopted. Furthermore, according to Pinto et al. (2016), the productivity of sprinkler-irrigated rice is a consequence of the combined effect of soil water tension and chemical properties, mainly because water is the medium for plant nutrient absorption.

A comparison of the PHSs of the two rice harvests obtained via the sprinkler irrigation method (Experiment 1) revealed that the 2012/2013 harvest presented relatively high values. This result is related to the influence of climatic factors that increase crop evapotranspiration. Notably, different management systems were applied to each harvest.

Figure 2 shows the results of the simplified blue water footprint and the green water footprint of Experiment 2, which were irrigated by flooding under different irrigation depth management practices, with the estimate corresponding to two rice harvests.

Figure 2. Simplified blue water footprint, green water footprint and simplified water footprint of Experiment 2 conducted under flood irrigation and different irrigation depth management practices.



Source: Adapted from Parfitt et al. (2018)
IC = continuous flooding; ICFI = continuous flooding with intermittent spraying; II 10 kPa = intermittent flooding with return irrigation with a soil water tension of 10 kPa in the aerated phase; II 40 kPa = intermittent flooding with return irrigation with tension of 40 kPa in the aerated phase; II 40/ICFI = intermittent flooding with return irrigation with tension of 40 kPa in the vegetative phase and with ICFI in the reproductive phase; II 40/10 kPa = intermittent flooding with return irrigation with tension of 40 kPa in the vegetative phase and with 10 kPa in the reproductive phase.

In the 2015/2016 harvest, the lowest $_{\text{green pH}}$ corresponded to continuous irrigation management (Figure 2). The lowest simplified $_{\text{blue pH}}$ corresponds to continuous irrigation management with an intermittent water supply, which was 268 m^3 t^{-1}. Furthermore, the highest simplified $_{\text{blue pH value}}$ refers to continuous irrigation management, which can be explained by the larger volume of water supplied via irrigation to maintain the water depth during the vegetative and productive phases of rice.

The comparison of the PHS of the four management systems revealed that the most satisfactory irrigation system was ICFI, as it presented a $_{\text{green pH}}$ similar to that of II 10 kPa and II 40 kPa, but its simplified $_{\text{blue pH}}$ was lower than that of the other systems (Figure 2). Similar to what occurred with the sprinkler irrigation method, the high grain yields obtained in the ICFI strongly reflect the PHS indicator, resulting in a lower volume of water required to produce each ton of rice.

In the 2016/2017 harvest, as shown in Figure 2, the $_{\text{green pH}}$ was lower for the IC and ICFI management systems, indicating that a smaller amount of water from precipitation was available to the plants during this period. Thus, the simplified $_{\text{blue pH}}$ was greater for these management systems, with the highest value corresponding to 419 m³ t^{-1}, a value corresponding to the IC management system.

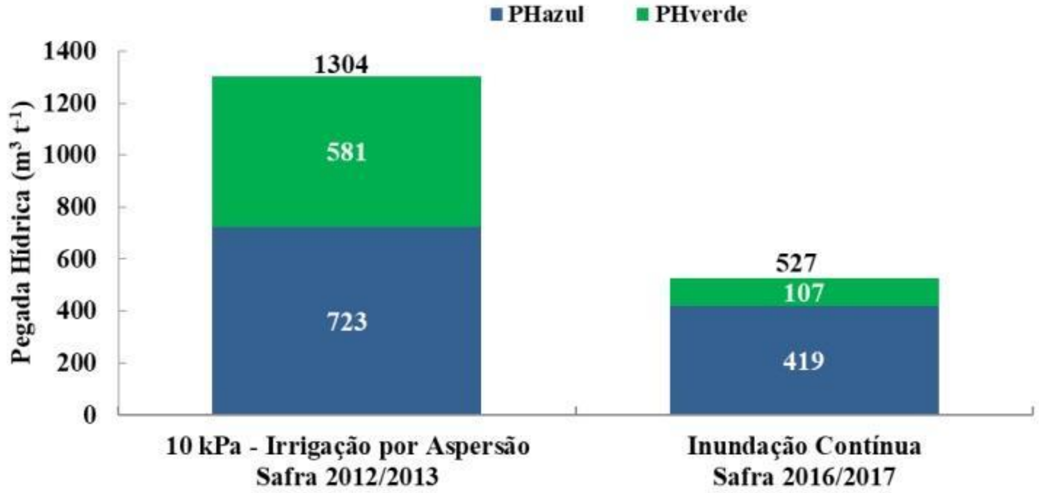
The analysis of the four management systems verified that the PHS presented similar values for the irrigation management systems IC, ICFI and II 40 kPa/ICFI, which were 527, 550 and 561 m³ t^{-1}, respectively; however, the II 40 kPa/ICFI system was more efficient. In addition, it is worth highlighting that the highest PHS value was obtained through the II 40/10 kPa management system, but it is possibly associated with the contribution of $_{\text{green PH}}$.

The management systems applied in the 2015/2016 and 2016/2017 harvests were mostly different, with the exception of the IC and ICFI management systems. The results demonstrated that a smaller simplified blue water footprint was required by the ICFI system, corresponding to 268 m³ t^{-1} in the 2015/2016 harvest and 376 m³ t^{-1} in the 2016/2017 harvest.

It was not possible to compare the other systems between harvests, but among the other management methods analyzed, II 40/ICFI presented the lowest simplified $_{\text{blue PH}}$, which corresponded to 268 m³ t^{-1}.

Figure 3 compares the simplified $_{\text{blue pH}}$ and $_{\text{green}}$ pH between Experiment 1 (sprinkler) and Experiment 2 (continuous flooding), considering only the irrigation management that presented the highest grain yield. The highest productivity value, in relation to the mobile lateral sprinkler irrigation system, was obtained through irrigation management based on a soil water tension of 10 kPa in the 2012/2013 harvest, and in the flood irrigation method, the highest productivity was obtained with the application of continuous irrigation (CI) management in both harvests.

Figure 3. Simplified blue water footprint, green water footprint and simplified water footprint of Experiment 1 (2012/2013 harvest) and Experiment 2 (2016/2017 harvest).



Source: Adapted from Pinto (2015) and Parfitt et al. (2018)

The green pH was greater in the sprinkler irrigation system (Figure 3) since the soil was not saturated and rainwater was used more effectively. The simplified blue pH was also greater for the sprinkler irrigation system, which was due mainly to the decrease in rice productivity under sprinkler irrigation (Table 2). According to Pinto et al. (2020), the productivity of sprinkler-irrigated rice corresponds to 87% of that of flood-irrigated rice.

The estimated PHS for the sprinkler irrigation system at 10 kPa was 1304 m^3t^{-1}, which was higher than that obtained for the IC system at 527 m^3t^{-1}. The PHS value for the continuous irrigation system was also lower than that reported by some authors for rice cultivation, in relation to the result of the green water footprint plus the blue water footprint. Marano and Filippi (2015) obtained a total sum of 914 m^3t^{-1} in an experiment with rice crops conducted in Argentina. The estimate by Chapagain and Hoekstra (2011) was 854 m^3t^{-1} in an experiment conducted in China. Zhuo, Mekonnen, and Hoekstra (2016) presented a result closer to that of this study of 639 m^3t^{-1} for experiments conducted in the Chinese region.

Importantly, the conditions evaluated in this study are experimental and do not accurately reflect those obtained in commercial crops, as evidenced by the high grain yields. Under these conditions, the PHS obtained in Experiment 2 (continuous flooding) was particularly beneficial, as it is a consolidated system adjusted for high yields, whereas the sprinkler-irrigated rice production system in southern Brazil is still evolving.

Higher PHS values in sprinkler irrigation systems are strongly associated with lower rice yields. However, it was not possible to identify the underlying cause of lower rice productivity under this system, as this is related to both irrigation management and factors such as genetic improvement of rice varieties for sprinkler irrigation, pest and weed control, soil fertility management, and climate conditions, among others, which have been evaluated by various researchers. However, the ideal management conditions capable of ensuring high rice productivity through sprinkler irrigation have not yet been defined, as the use of this system in this crop is still in its infancy.

With respect to continuous irrigation, rice productivity is greater because of water availability and because the factors that affect grain yield are controlled when this system is adopted.

Intensified production systems, with high levels of technological adoption and well adjusted for flood irrigation, despite requiring greater water volumes, tend to produce more grains per unit area and favor lower water footprint values. Therefore, it is important to conduct research aimed at adjusting the sprinkler-irrigated rice production system to achieve higher yields and lower water footprint values.

This study assessed the water footprint of irrigated rice in southern Brazil by simplifying the traditional water footprint estimation methodology. Notably, rice water footprint values vary considerably depending on the region evaluated, crop management, and irrigation method. Xinchun et al. (2018) conducted a literature review of the green and blue water footprints estimated by various researchers, each obtained for a specific location, corresponding to a total of fourteen regions, where the sum of the blue and green fractions ranged from approximately 771 to 2005 $m^3\ t^{-1}$. Thus, it appears that there is no specific value that represents the water footprint of rice crops worldwide, which highlights the importance of studies to understand the behavior of the water footprint in Rio Grande do Sul and Brazil.

6 CONCLUSIONS

The soil water tension was maintained closer to the soil saturation conditions, at 20 kPa in the 2011/2012 harvest and 10 kPa in the 2012/2013 harvest, resulting in a smaller simplified water footprint of irrigated rice for the sprinkler irrigation method.

Among the flood irrigation methods, the management of the irrigated sheet by continuous flooding presented a smaller simplified water footprint.

Compared with the sprinkler irrigation method, the continuous flood irrigation method resulted in a smaller simplified water footprint (at the 10 kPa stress limit).

Grain productivity had a strong influence on the simplified water footprint values of irrigated rice.

7 ACKNOWLEDGMENTS

The authors would like to thank Embrapa Clima Temperado for the technical support and infrastructure made available to carry out the preliminary work that served as the basis for this study.

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