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Economically optimal water depth and grain yield of common bean subjected to different irrigation depths

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ABSTRACT

Common bean crop plays an important role in the world, not only in economic aspects but also in social development. The objective of this study was to evaluate the grain yield and the economically optimal water depth which reflects the maximum technical efficiency of the common bean crop. The experiment was conducted in greenhouse, in Alegrete - RS, from February to May 2016. A completely randomized design was used, consisting of five water replacement treatments (25, 50, 75, 100 and 125% crop evapotranspiration - ETc) and four replicates. Based on the obtained results, both water deficit and water excess directly affected the final grain yield of the crop. Maximum grain yield was 3,554.1 kg ha^{-1}, obtained by applying 492.72 mm (100% ETc). On the other hand, the economically optimal water depth was estimated at 91.2% ETc, indicating that water depths above this value are not suitable for maximum technical efficiency in the common bean crop under these conditions. It was concluded that the water depth equivalent to 100% ETc maximizes grain yield for the region of Alegrete-RS, and irrigation is considered a solution in the water supply to the common bean crop during critical periods.

Palavras-chave:
Phaseolus vulgaris L.
manejo de água
componentes de produtividade

Lâmina ótima econômica e produção de grãos de feijão submetido a distintas lâminas de irrigação

RESUMO

O cultivo do feijão apresenta importância mundial, tanto no que se refere ao desenvolvimento econômico, quanto ao caráter social. O trabalho foi realizado com o objetivo de avaliar a produção de grãos e a lâmina ótima econômica que reflete a máxima eficiência técnica da cultura do feijão. O experimento foi conduzido em casa de vegetação, em Alegrete – RS, no período de fevereiro a maio de 2016. Utilizou-se um delineamento inteiramente casualizado, composto por cinco tratamentos de reposição de água (25, 50, 75, 100 e 125% da evapotranspiração da cultura) e quatro repetições. Através dos resultados obtidos, permitiu-se observar que tanto o déficit hídrico, quanto o excesso de água, afetaram diretamente na produção final de grãos da cultura. A máxima produção de grãos foi de 3554,1 kg ha^{-1}, aplicando-se 492,72 mm (100% da evapotranspiração da cultura). Em contrapartida, a lâmina ótima econômica foi estimada em 91,2% de reposição da ETc, indicando que lâminas acima desse valor não são adequadas visando à máxima eficiência econômica da irrigação, para a cultura do feijoeiro. Deste modo, conclui-se que a lâmina que representa 100% da evapotranspiração da cultura maximiza a produção de grãos para a região de Alegrete, RS, sendo a prática da irrigação considerada uma solução no suprimento de água para a cultura do feijão, nos períodos críticos.

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Introduction

Among the climatic factors that most influence common bean yield, scarce or poorly distributed rains are the main cause of unsuccessful production (Pereira et al., 2014), thus justifying the aversion of famers to the risks involved in this activity. Because of that, irrigation is an alternative to supply water to plants, in order to meet water demand in the most critical periods, i.e., when the water precipitated as rain is not enough. Consequently, this practice is widely used by various producers (Lopes et al., 2011).

Regarding the production of common bean grains, the most sensitive component to crop water status is the number of pods per plant. According to Guimarães et al. (2011), this component is more intensely affected than the number of grains per pod, which leads to the inference that water deficit acts more intensely on the abscission of flowers and pods than on pollen sterility, which determines lower number of grains per pod. Consequently, the higher the number of pods per plant, the greater the production, provided that these pods are filled with healthy grains.

In the current context, to achieve the goals of higher yields, product quality and efficient use of water resources, one should take into consideration the need for optimizing irrigation water management (Singh & Panda, 2012).

Considering the financial aspect, most irrigation systems nowadays are operated by electricity, so that the operation costs of irrigation are basically represented by the cost of the electricity used. In the common bean crop, sprinkler irrigation systems are normally used and, according to Paz et al. (2002), Figueiredo et al. (2008) and Ramos et al. (2012), the estimated cost of water (R\$ mm^{-1} ha^{-1}) is about 1.15 and 2.70, 2.66, 2.80 and R\$ 1.56 mm^{-1} ha^{-1}, respectively, considering a variability with respect to operation times of the systems and different localities in the territory.

Therefore, given the economic importance of the crop, in addition to studies aiming to optimize bean irrigation planning and demonstrate its production capacity, the present study aimed to evaluate the effect of different water depths on bean grain yield and determine the water depth with maximum economic efficiency for this crop.

Material and Methods

The study was carried out in a greenhouse in the municipality of Alegrete – Rio Grande do Sul, Brazil (29° 71' 16" S; 55° 52' 61" W; 121 m), which has a humid temperate climate, with hot summer and well-defined seasons (Cfa, Köppen).

The experiment was conducted from February to May 2016, which comprehends the sowing in the 2nd season (period with lower rainfall). Data relative to climatic conditions (maximum and minimum daily values of temperature and relative humidity) were obtained using a digital thermo-hygrometer installed close to the experimental bench.

The experiment consisted of a completely randomized design, formed by five treatments of irrigation (25, 50, 75, 100 and 125% crop evapotranspiration - ETc) and four replicates. Plastic pots, 33 cm diameter and 30 cm height, were arranged on a bench at 30 cm height from the soil. The pots were filled with soil from an arenic dystrophic Red Argisol, São Pedro mapping unit (Streck et al., 2008), using the amount of 0.018 m^3 per pot.

Physical analysis carried out according to Donagema et al. (2011) revealed that the soil has a sandy loam texture (9.66% - coarse sand, 65.75% - fine sand, 21.95% - silt and 2.64% clay), and soil bulk and particle densities correspond to 1.64 and 2.58 kg dm^{-3}, respectively. For soil chemical analysis, three disturbed soil samples were collected in the 10-30 cm layer, as recommended by the Commission of Soil Chemistry and Fertility (CQFS, 2004). The following data were obtained: intermediate pH (5.5), low organic matter content (1.25%), intermediate CEC (5.62 $cmol_c$ kg^{-1}) with low clay content, intermediate phosphorus content (0.25 mg dm^{-3}), very high potassium content (31.2 mg dm^{-3}) and high contents of calcium and magnesium (2.61 and 0.96 $cmol_c$ kg^{-1}, respectively).

Fertilization was performed immediately after sowing, equivalent to 360 kg ha^{-1}, using the formulation 00-25-20. At 25 days after sowing, nitrogen was applied in all treatments, 80 kg ha^{-1}.

The experiment used cultivar BRS Valente, with medium cycle, considered as day-neutral, i.e., it does not depend on photoperiod for flowering. Five seeds were planted per pot and, after emergence, they were manually thinned to obtain a population equivalent to 350 thousand plants ha^{-1}. Germination occurred at 4 days after sowing. Irrigation management was based on a fixed interval of 4 days. Water depths were applied based on ETc data, according to Eq. 1 (Doorenbos & Pruitt, 1977).

$$ETc = ETo\ kc \tag{1}$$

where:

ETc - crop evapotranspiration, mm;

ETo - reference evapotranspiration, mm; and,

kc - crop coefficient (initial – 0.69, intermediate – 1.28 and final – 1.04).

Water was manually applied in the pots, using a graduated cylinder. Thus, the evapotranspired depth was converted to milliliters, considering the area of the pot.

Reference evapotranspiration was estimated by the indirect method of Benevides & Diaz (1970), according to the availability of meteorological data inside the protected environment, using Eq. 2.

$$ETo = 0.67\ 10^{\left(\frac{7.5T}{T+237.5}\right)}\left(1-0.01RH\right)+0.12T-0.38 \tag{2}$$

where:

T - mean temperature, °C; and,

RH - mean relative air humidity, %.

When plants reached physiological maturity and moisture content adequate for harvest, production components were evaluated: number of pods per plant, number of grains per pod and mean grain weight.

The yield for each treatment was estimated by Eq. 3:

$$GY = \frac{10}{0.01 - U}\ NPL\ NPP\ NGP\ MGW \quad (3)$$

where:

GY - grain yield, kg ha^{-1};
U - grain moisture for harvest, 13%;
NPL - number of plants, m^{-2};
NPP - number of pods per plant;
NGP - number of grains per pod; and,
MGW - mean grain weight, g.

Grain moisture content at harvest was determined by the direct method of drying in forced-air oven at +/- 105 °C for 24 h.

Production function was obtained by regression analysis between the dependent variable (yield "Y", in kg ha^{-1}) and the independent variable (water depth "w") through a second-order polynomial model proposed by Oliveira et al. (2011), according to Eq. 4.

$$Y = a + bw + cw^2 \quad (4)$$

where:

Y - yield, kg ha^{-1};
w - water depth, mm; and,
a, b and c - coefficients of the regression equation for grain yield.

Since the cost of the water (common good of all, invaluable) necessary for irrigation was totally composed of the cost of electricity (R$ mm^{-1} ha^{-1}), Lima et al. (2009) proposes that it can be obtained through the product of the specific energy dissipated in the sprinkler irrigation system (kWh mm^{-1} ha^{-1}) by the number of hours of operation and by the mean cost of electricity (R$ kWh^{-1}).

Thus, only the costs for water supply were considered, whereas the other factors involved in crop production, such as inputs, fertilizers and machinery, remained fixed at an optimal level and equal for all treatments.

To obtain the water depth corresponding to maximum return or economic efficiency (MEE), the model to be minimized is the one of net revenue or net profit, represented by Eq. 5:

$$L = \left(a + bw + cw^2\right) Py - w\ Pw \quad (5)$$

where:

L - net revenue or net profit, R$;
Py - product's sale price, R$ kg^{-1};
w - water depth, mm; and
Pw - water depth application cost, R$ mm^{-1} ha^{-1}.

By solving the first derivative of Eq. 5 with respect to the applied water depth and making it equal to zero, it is possible to obtain the water depth corresponding to maximum return, or water depth corresponding to maximum economic efficiency (MEE), expressed by Eq. 6:

$$W = \frac{\frac{Pw}{Py} b}{2c} \quad (6)$$

where:

W - economically optimal water depth, mm.

The prices of the applied water depth (Pw) were those obtained from the bibliography and previously cited (Paz et al., 2002; Figueiredo et al., 2008; Ramos et al., 2012), considering mean values for water costs within a range from 0.30 to 1.50 U$ mm^{-1} ha^{-1}.

Product price (Py) was obtained through the mean selling price per 60-kg sack for the state in September 2016, approximately R$ 217.50 (U$ 68.40), obtaining the value for the kilogram of the product of U$ 1.14, paid to the producer in October 2016.

In this context, water price was varied by $ 0.30 while product price remained fixed, which led to eleven ratios (Pw/Py), used in Eq. 6.

To evaluate the occurrence of water deficit or water excess in the long term, the historical series of rainfall and crop evapotranspiration were evaluated. A 10-year period (2007-2016) was considered in the present study to verify the magnitude of the oscillations in water deficit/excess. Two scales were considered: i) total value for the cultivation period, and ii) values obtained by crop stage (Stage 1 – germination to flowering; Stage 2 – flowering to grain filling; and Stage 3 – grain filling to physiological maturity). The climatic data of the historical series were obtained from the Automatic Meteorological Station of Alegrete, RS, installed at the Farroupilha Federal Institute – Campus of Alegrete, operated by the National Institute of Meteorology.

Analysis of variance by F test ($p > 0.05$) was used to interpret the results of the significance level, using the statistical package Sisvar 5.6 (Ferreira, 2010). When there was significant difference between treatments, regression analysis was carried out and graphs were constructed using the program Sigma Plot 13.0.

Results and Discussion

The results of the analysis of variance for the different water depths and their respective significances are presented in Table 1.

Figure 1 shows the response to the irrigation applied in the common bean crop for the number of pods per plant (Figure 1A)

Table 1. Summary of the analysis of variance for the number of pods per plant (NPP), number of grains per pod (NGP), mean grain weight (MGW) and final grain yield (GY) for the different water depths

Source of variation	DF	Mean square			
		NPP	NGP	MGW (g)	GY (kg ha^{-1})
Water depths	4	15.465*	0.4957^{ns}	0.0001^{ns}	2205722*
Error	15	0.6089	0.2328	0.0000	117631
CV %	-	9.38	13.75	3.71	13.06
Overall mean	-	8.31	3.51	0.221	2626.37

*Significant by F test at 0.05 probability level; ^{ns}Not significant by F test at 0.05 probability level

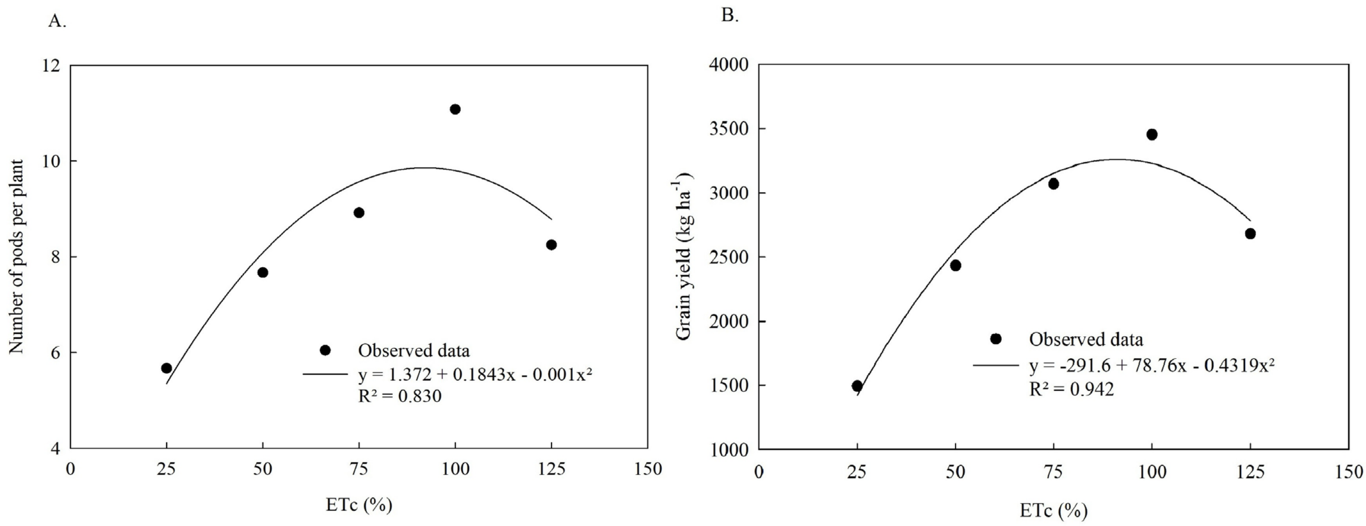

Figure 1. Number of pods per plant (A) and final grain yield (B) in the common bean crop as a function of different water depths

and final grain yield (Figure 1B), demonstrating that water deficit and water excess caused significant effects.

Highest number of pods per plant was found in the treatment corresponding to the replacement of 100% ETc, with mean of 11.08, the closest value to the result of the maximum economic efficiency, 10.10 pods per plant. Water excess in the present study (125% ETc) resulted in 27.15% reduction in this parameter compared with the water depth of maximum economic efficiency, which was 91.2% ETc.

The result obtained here agrees with that of Monteiro et al. (2012), who observed the same behavior in this parameter for irrigated beans, increasing from 8.73 to 17.05 pods plant^{-1} with water depths of 179.5 and 357.5 mm, and decreasing to 12.63 pods as the water depth increased to 406.2 mm.

Torres et al. (2013) observed that the number of pods per plant was highest with the replacement of 100% ETc, 10.37 pods per plant, for the cultivar Pérola, studying different replacement levels and different soil covers. These authors also point out that the increase in water depth (130 and 160% ETc) leads to reduction in this parameter, as found in the present study.

Acosta-Gallegos & Shibata (1989) highlight that the number of pods per plant is determined in the initial flowering stage of the crop, thus being sensitive to water deficit.

Number of grains per pod and mean grain weight did not differ significantly between water depths. Guimarães et al. (2011) considered water deficit as more relevant for the number of pods per plant than for pollen sterility, which will determine the reduction in the number of grains per pod.

The number of grains per pod showed mean value of 3.54, which agrees with the results reported by Monteiro et al. (2012), who observed values of 3.49 to 4.61, at different levels of water replacement. Mean grain weight was equal to 0.22 g, coinciding with the value indicated by the information about the cultivar, thus demonstrating that this parameter is determined by genetic factors.

Final grain yield increased with the increment in water depths (Figure 1B), reaching maximum value at 91.2% ETc, and decreased until the water depth of 125% ETc, fitting to a quadratic polynomial function.

Highest grain yield in the common bean crop for the water depth of 91.2% ETc was estimated at 3265.4 kg ha^{-1}, with the use of 492.72 mm of water along the entire crop cycle. A reduction in yield was observed for the water depth of 125% ETc, which led to mean yield of 2680.9 kg ha^{-1}. However, the value of 1493.5 kg ha^{-1} caused by the 25% ETc treatment showed the most expressive reduction, demonstrating that the cumulative water deficit compromised plant physiology and consequently led to reduction of yield. On the other hand, excess moisture around the root system probably hampered aeration, causing physiological anomalies and possible leaching of the nutrients provided to plants, increasing the costs of the crop without benefits and wasting water.

The results for bean grain yield corroborate those obtained by Torres et al. (2013), who studied water depths of 40, 70, 100, 130 and 160% ETc, in soil classified as dystrophic Red Latosol, and found increase of yield up to 100% ETc and decrease as the water depth further increased (130 and 160%). These authors also explain that water depths exceeding 100% ETc probably caused oxygen deficiency in the soil during certain periods, leading to reduction in microbial activity and culminating in reduction of yield.

The highest yield obtained here agrees with that found by Carvalho et al. (2014), who tested different irrigation managements in direct seeding system for the cultivar IAC Alvorada in the region of Botucatu-SP and obtained 3638.0 kg ha^{-1}, with replacement of 100% ETc. Santana et al. (2008) observed increase in bean yield as a function of water replacement, reaching maximum of 3,377.4 kg ha^{-1} with a volume corresponding to 100% of the water consumed, and reduction in grain yield of approximately 799 kg ha^{-1} at 160% water replacement. For Santana et al. (2014), the difference observed between 100% (433.50 mm) and 130% ETc led to a reduction of 1063.0 kg ha^{-1}.

Optimal water depth to obtain maximum economic efficiency is presented in Figure 2.

According to the equation in Figure 2, when Pw/Py is equal to zero, the optimal water depth leading to maximum economic efficiency is 91.2% ETc; consequently, higher water depths are economically inadequate. Thus, as Pw/Py increases (increase

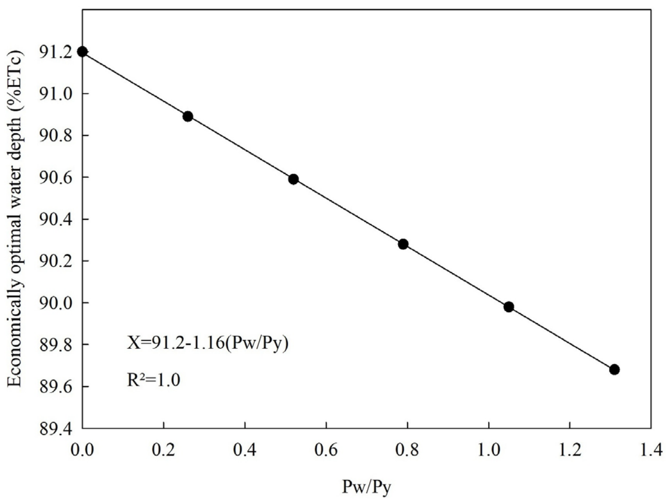

Figure 2. Economically optimal water depth as a function of the ratio between water price (Pw) (U$ mm^{-1} ha^{-1}) and the price of 1 kg of beans (Py) (U$), for the marketable yield

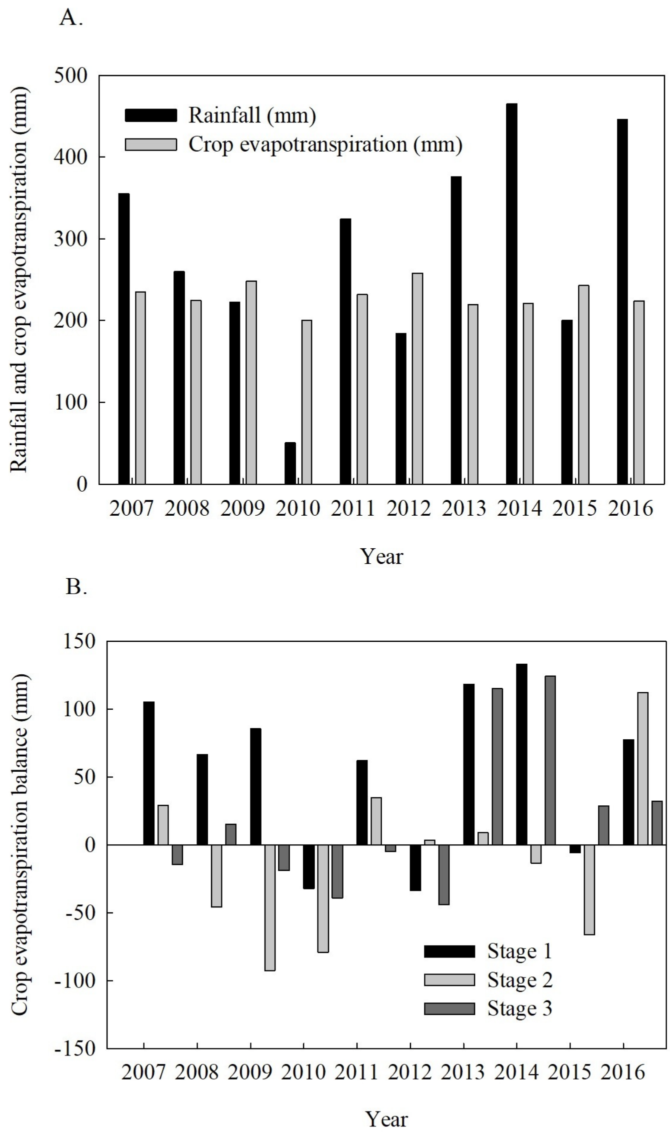

Figure 3. Oscillation of rainfall and crop evapotranspiration (A) and crop evapotranspiration balance in relation to rainfall in the different growth stages of the crop (B) in the historical series (10 years)

in water cost), different economically viable water depths are obtained, which lead to maximum economic efficiency.

Locatelli et al. (2014), studying irrigation efficiency in different cowpea cultivars in the Cerrado region, with water depths of 30, 60, 90, 120 and 150% ETo, concluded that economically optimal water depths leading to maximum technical efficiency for the cultivars BRS Guariba and BRS Nova Era were 74.3 and 94.02%, respectively, highlighting that water depths above these values are not adequate for maximum technical efficiency.

Given the above, varying only water price and keeping product price unchanged, the economically optimal water depth (%ETc) to be applied should be that at which the ratio between water depth cost (Pw) and crop yield is minimized, aiming at maximum profit for the producer in the agricultural activity. It should also be pointed out that the obtained and previously discussed data result from using the method of Benevides & Diaz (1970) to determine ETo and, consequently, to determine ETc, which leads to possible differences when water depths based on other methods are applied in the irrigation management.

Figure 3 shows the oscillations between rainfall and crop evapotranspiration (Figure 3A) and crop evapotranspiration in the different stages (Figure 3B), calculated in the historical series (10 years), for the same period of study.

Irregularity and variability in the rainfalls between seasons were observed during the different years studied, which leads to instability in the yield of crops such as common bean. Rainfalls from February to May along the studied years encompass a scale from 50.2 to 465.2 mm, with mean value of 296.84 mm, which demonstrates deficit of 40%, compared with the water depth leading to highest grain yield. For the years 2009, 2010, 2012 and 2015, when water deficit occurred, there were negative differences of about 25.70, 150.26, 73.81 and 42.70 mm, respectively. Regarding water excess, in the years 2013, 2014 and 2016, the crop would be directly affected by the excess rainfall, which would lead to reduction in grain yield according to the results of the present study.

For the water demand in the different crop stages (Figure 3B), oscillations occurred in the initial (stage 1 - emergence to flowering), intermediate (stage 2 - flowering to grain filling) and final (stage 3 - grain filling to maturity) periods of the crop cycle.

Considering the most critical period with respect to the lack of water, from flowering to grain filling, the bean crop would undergo water deficit in 50% of the historical series, comprehending the years 2008, 2009, 2010, 2014 and 2015, for the studied region.

Conclusions

1. Irrigation equivalent to the replacement of 100% ETc maximizes grain yield of the common bean crop for the region of Alegrete, RS.

2. Economically optimal water depth for the studied conditions was 91.2% ETc. As the Pw/Py ratio increases, there is a reduction in the economically optimal water depth.

3. Irrigation proves to be an important solution in supplying the water volume demanded by the crop during critical periods, in which rainfall does not occur or is poorly distributed.

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